PB-222 075

LOW NOx EMISSION COMBUSTOR FOR AUTOMOBILE GAS TURBINE ENGINES

UNITED AIRCRAFT OF CANADA LTD.

PREPARED FOR
ENVIRONMENTAL PROTECTION AGENCY

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LOW NOx EMISSION COMBUSTOR FOR AUTOMOBILE GAS TURBINE ENGINES

FINAL REPORT

FEBRUARY 1973

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The emission levels that could be reached by development on two combustors representing a 12:1 pressure ratio simple cycle gas turbine, and a 5:1 pressure ratio regenerative cycle gas turbine, both for automotive application were evaluated. Goals were to equal or better the EPA 1975-76 Federal Emission Standards for automobiles. Some 60 atmospheric rig tests were carried out on the simple-cycle combustor whilst 39 atmospheric rig tests were carried out on the regenerative cycle combustor. Some 430 pressure test points involving over 200 modifications to combustor geometry were run. Various fuel injection methods were employed, such as pressure atomizing, air-assisted pressure atomizing and air-blast atomizing. For reasons of reliability and primary zone leanness, the air-blast atomizer was the final selection. The best results were obtained by the introduction of sufficient air to provide a lean head end (in the form of 3 stages of swirl) while maintaining fairly high temperatures in the intermediate zone, the remainder of the air being introduced into the dilution zone. Effects of outside parameters - viz. inlet humidity and regenerator bypass - on combustor emissions were also evaluated. Judicious alterations to head end aerodynamics combined with use of dependable fuel atomizing techniques (e.g., air-blast atomizers) can result in substantial reduction of emissions from simple geometry combustors.

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NOMENCLATURE

C	Empirical Constant
D	Diameter, Inches
EI	Emission Index, lbs of pollutant/1000 lbs fuel
ER	Emission Ratio $\left(\frac{\text{Measured Emission Index}}{\text{Target Emission Index}}\right)$ Dimensionless
far, f/a	Fuel-air ratio, W_f/W_a
FDC	Federal Driving Cycle
FN	Flow Number, $\left(\frac{\text{lbs}}{\text{hr}\sqrt{\text{lbs per in}^2}}\right)$
K_f	Forward Reaction Constant, Cm^3/mole-sec
L	Length, inches
PPM	Parts per Million
P	Pressure, psia
SHP	Shaft Horsepower
T	Temperature, °F, °R
VE	Vehicle Economy, Miles per Gallon
W	Flow Rate, lbs/sec
ΔP	Pressure drop, psi
ϕ	Equivalence Ratio, dimensionless
α	Specific Humidity, lb water/lb air

SUBSCRIPTS

a	Air
f	Fuel
in	Combustor inlet
out	Combustor outlet
PZ	Primary Zone
IZ	Intermediate Zone
DZ	Dilution Zone

FOREWORD

This report No. APTD-1457 entitled "Low NO_x Emission Combustor for Automobile Gas Turbine Engines" is the final report under E. P. A. Contract No. 68-04-0015.

The period of performance was from 9 August 1971 to 31 January 1973 including this final report.

Several modifications to the Contract have been made during the term of the Contract. These are as follows:

1. Redesignation of Class B Combustor (Simple Cycle) to Class UB and Class A Combustor (Regenerative Cycle) to Class A/Mod.
2. Modifications to the final test procedure to accommodate the changes in para. (1), Attachment A, October 15, 1971.
3. Re-scheduling of the program to suit changes in para. (1) and (2).
4. Modifications of test procedure to allow more development work, November 6, 1972.

The technical contents of this report reflect the above changes agreed to between U.A.C. and E.P.A.

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SUMMARY

Under contract with the U.S. Environmental Protection Agency, a program was carried out to evaluate the emission levels that could be reached by development on two combustors representing a 12:1 pressure ratio simple cycle gas turbine, and a 5:1 pressure ratio regenerative cycle gas turbine, both for automotive application. Goals were to equal or better the EPA 1975-76 Federal Emission Standards for automobiles. These standards specify the following maximum allowable levels of vehicle emissions:

Oxides of Nitrogen (NO_x) - 0.4 gms/mile
Carbon Monoxide (CO) - 3.4 gms/mile
Hydrocarbons (UHC) - 0.41 gms/mile

United Aircraft of Canada Ltd. was the prime contractor and United Aircraft Research Laboratories was sub-contracted. Initial design and atmospheric rig development were conducted by UACL, and UARL provided theoretical models of emission formation. Pressure testing was conducted by and at UARL, under the direction of UACL.

Some 60 atmospheric rig tests were carried out on the simple-cycle combustor (designated ~~Class UB~~) whilst 39 atmospheric rig tests were carried out on the regenerative cycle combustor ~~(designated Class A/Mod) at UACL~~. Some 430 pressure test points involving over 200 modifications to combustor geometry were run at UARL.

Various fuel injection methods were employed, such as pressure atomizing, air-assisted pressure atomizing and air-blast atomizing. For reasons of reliability and primary zone leanness, the air-blast atomizer was the final selection.

The concept of a lean head end was pursued ~~throughout the program~~ for both combustors, but the best method of achieving this was not determined until late in the program, and time and funding did not permit optimization of the approach.

Essentially, the best results were obtained by the introduction of sufficient air to provide a lean head end (in the form of 3 stages of swirl) while maintaining fairly high temperatures in the intermediate zone, the remainder of the air being introduced into the dilution zone.

The combustors were rig tested for emissions in the following modes as specified by EPA.:

1) The simulated Federal Driving Cycle (FDC),
2) Steady Speed Mode, and
3) Range Mode (Class UB only).

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1) The simulated Federal Driving Cycle (FDC),
2) Steady Speed Mode, and
3) Range Mode (Class UB only).

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Effects of outside parameters - viz. inlet humidity and regenerator bypass (A/Mod) - on combustor emissions were also evaluated.

The best emission values achieved under this contract are summarized below and are compared to Chrysler data published Dec. '72, which well represents current state of the art.

	Federal Standards 1975-76 gms/mile	Program Achievements gms/mile		Chrysler Data (13) gms/mile
		Class UB	Class A/Mod	
Nitrogen Oxides*	0.4	0.52	0.58	2.7
Carbon Monoxide	3.4	3.64	6.18	4.3
Hydrocarbons	0.41	0.49	0.06	1.1
Assumed Vehicle Economy on Simulated Federal Driving Cycle		8.6	12.7	-

* Corrected to Standard Humidity

The emission values quoted above were achieved with simple and practical hardware designs which appear to be adaptable to any can-type combustor. Both combustors had excellent stability indicating that further development could result in substantial further emission reduction. Final detailed development to achieve full roadworthy combustors might lead to some increase in emissions. Severe transients during operation of the regenerative combustors will make it particularly difficult to duplicate rig results in actual driving conditions.

The extent of improvements in emissions accomplished under the program may be seen from the following table which refers to the development phase under representative operating pressures.

EMISSION INDICES

	Class UB, FDC #2†		Class A/Mod, FDC #2‡	
	Initial	Final	Initial	Final
NO_x*	0.76	0.40	0.67	0.39
CO	12.67	3.38	8.30	12.00
UHC	1.15	0.07	0.16	0.06

* Corrected to Standard Humidity
† Refer to Table 4-2
‡ Refer to Table 4-13

The program has demonstrated that judicious alterations to head end aerodynamics combined with use of dependable fuel atomizing techniques (e.g., air-blast atomizers) can result in substantial reductions of emissions from simple geometry combustors. It is felt that a continuation of developmental effort on the UB combustor will result in emission levels which will meet the 1976 Federal Standards on the test rig with some modest margin for actual driving conditions. The A/Mod combustor can be further improved, but to achieve Federal standards with adequate allowance for the severe transients faced by regenerative/recuperative combustors is likely to require variable combustor geometry and/or partial heat exchanger bypass to the combustor primary zone.

1. INTRODUCTION

The permissible levels of automobile exhaust emissions set by Congress and EPA for 1976(1)* are widely recognized as extremely stringent and difficult to meet. The generally favorable emission characteristics of continuous combustion systems have prompted increased interest in the gas turbine as a potential automobile engine.

Comprehensive design analysis of gas turbine engines for automotive propulsion and a manufacturing cost study for such engines were undertaken by United Aircraft Corporation under separate contracts with EPA(2, 3, 4). Those studies identified single-shaft, simple-cycle engines of 10 - 12:1 pressure ratio as having excellent potential for low cost and for low emissions, particularly of NO_x the most difficult pollutant. The engines (identified as SSS-10 and SSS-12 respectively) were based on advanced aerospace technology from UACL(5). The claims for low-emission potential of this engine were carefully examined by General Motors (6) who concluded that the engine should have attractive NO_x emissions but cautioned that the CO emissions could be many times the requirement.

A research program for development of two types of low NO_x combustors was sponsored by the Environmental Protection Agency at United Aircraft of Canada (UACL) with major support from United Aircraft Research Laboratories (UARL). The aim of the program was to develop combustors for (i) Class A/Mod, low pressure ratio (5:1) regenerator cycle gas turbine engine and (ii) Class UB, high pressure ratio (12:1) simple cycle gas turbine engine (UAC SSS-12).

The program started in August 1971 and concluded in December 1972. Work was equally divided between UACL and UARL. UACL as prime contractor had design and development responsibility and conducted atmospheric testing, while UARL provided sophisticated emissions modeling and conducted the full pressure testing and final evaluation. The larger portion of the effort was placed on the Class UB simple cycle combustor, due in part to its superior potential for low emissions and also, being first studied, techniques to reduce emissions were developed on it. Class UB development resulted in integrated emission levels over the simulated Federal Driving Cycle very close to targets. Major reductions were accomplished on the Class A/Mod regenerator combustor due largely to the technology acquired from Class UB, but the integrated emission levels were substantially above targets. It is believed, however, that with a fairly minor extra effort, emission levels very close to EPA target levels can be achieved. A fixed geometry combustor would suffice for Class UB while Class A/Mod combustor may need variable geometry of a simple practical form to achieve target emission levels.

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* The numbers in parentheses indicate References listed on page R-1.

TABLE 1-1 1976 EMISSION STANDARDS*

(a)	Hydrocarbons	0.41 gram per Vehicle Mile
(b)	Carbon Monoxide	3.40 grams per Vehicle Mile
(c)	Oxides of Nitrogen	0.40 gram per Vehicle Mile

* Federal Register November 15, 1972

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2. SCOPE OF WORK

The investigations described in this report were conducted at United Aircraft of Canada in Longueuil, Canada, and at United Aircraft Research Laboratories in E. Hartford, Conn., under sponsorship of the Environmental Protection Agency. Development was aimed toward reducing emissions from two combustors for (1) gas turbine Class A/Mod, low pressure ratio (5:1), regenerated, and (2) gas turbine Class UB, high pressure ratio (12:1), non-regenerated. The work was undertaken in four phases.

Phase 1: Basic Combustor Designs

The two combustors were designed making use of best conventional combustor design philosophies. While the basic profile design made use of well-known design practices,(7) the flow splits in the different regions of the combustors were decided on estimates of primary and intermediate zone equivalence ratios, which were thought to result in low overall emissions. For Class UB combustor, the philosophy was to start with a primary zone equivalence ratio $\phi_{PZ} = 0.95$ which is good for low CO, and optimize for NO_X by reduced residence time and further leaning of primary zone as required. The intermediate zone was to be maintained at a temperature high enough to consume CO, UHC, but not for generation of NO_X. The A/Mod Combustor was initially designed for a leaner head end - $\phi_{PZ} = 0.85$.

Water modelling was used extensively in determining flow ratios. Attempts were also made to estimate residence times from the water model, but these estimates are considered very approximate since actual flow conditions cannot be simulated completely on a water model.

Some of the principal design criteria are discussed under Chapter 4 of this report.

Phase 2: EPA Approval

EPA's approval of the basic designs was obtained from the project officer as required contractually.

Phase 3: Fabrication and Set-up

The test facility at UACL was used for atmospheric development of the two classes of combustors. A sketch of the installation is shown in Figure 2.1. The atmospheric test facility provides up to 0.5 lbs/sec of unvitiated air at temperatures up to 1400°F. An electrical (resistance type) heater was used to raise the air temperature to required levels. A new set of gas analysis instrumentation was procured for execution of the program. Details of emission instrumentation used by UACL are described in Section 3.3 of this report.

The facility at UARL served for pressure testing and development on both classes of combustors. Heating was accomplished by electrical heaters up to 1200°F, and a combined oil-electrical heating scheme for temperatures up to 1350°F. Details of the UARL facilities are described in Section 3.4.

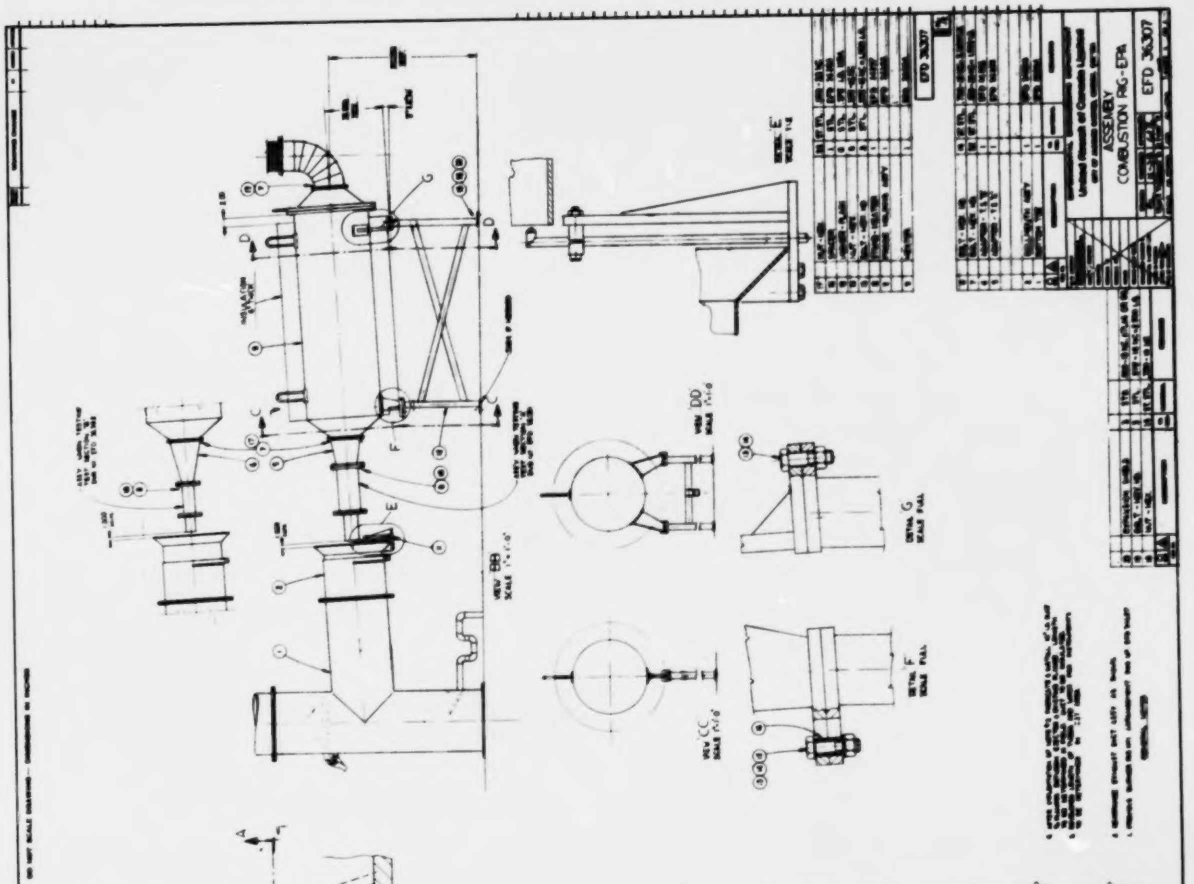
In both the test facilities, burning zones were observed through inspection windows. In the pressure facility at UARL ease of emission sampling was sacrificed in favor of a sight glass allowing full on-axis viewing of the combustor. This enabled an invaluable qualitative understanding of the flame characteristics as related to combustor emissions. Temperature distribution on combustor walls were studied using temperature sensitive paint (Thermindex OG-6). Exhaust temperature profiles were measured using thermocouples.

Phase 4: Test and Evaluation

The cost effectiveness of atmospheric testing showed up quite well on both the UB and A/Mod development programs. Substantial improvements in emission levels were achieved atmospherically with turn-around rates of 4 to 5 modifications a day. However with the leaning of head end, stability at atmospheric pressure was marginal and hence the full potential of lean primary zone could not be explored. Intensive development under pressure had to be resorted to instead of only the minimum development and final evaluation originally planned.

Full pressure tests showed that good stability could be maintained even at low fuel-air ratios in the primary zone. More than 200 modifications were evaluated at full pressure on Class UB combustor and about 25 on Class A/Mod flame tube. Final evaluation was on a reduced test matrix, as agreed by EPA. Analytical modelling was used extensively on Class UB combustor program. This was found to be a useful tool in predicting effect of pressure on emissions and also the effect of ambient humidity.

FIGURE 2.1 LAYOUT OF RIG FOR ATMOSPHERIC TESTS


ASSEMBLY
COMBUSTION RIG-EPA
EFD 36307
VIEW AA
VIEW BB
VIEW CC
VIEW DD
DETAIL E
DETAIL F
DETAIL G

3. FACILITIES AND INSTRUMENTATION

A brief description of some of the facilities and emission measuring instrumentation is given in this Chapter.

3.1 Atmospheric Test Facility – UACL

This facility at UACL was set up by modifications to an already existing burner test stand, Figure 2.1. An electrical resistance heater was installed to provide for unvitiated air flows up to 0.5 lbs/sec at inlet temperatures up to 1400 °F. Air was supplied by a blower to static pressures up to 40" water and air flow was metered by an orifice plate designed to B.S.F. practice. The transition piece between the heater and the test section (Figure 2.1) was provided with screens to reduce asymmetry and turbulence in the flow stream. The air temperature (T_{in}) and static pressure (P_{in}) were recorded in the test section upstream of the combustor (Figure 3.1). Downstream of the combustor the total pressure (P_{out}) and temperature (T_{out}) were measured with multi-point thermocouples. Emission sampling was done with two types of sampling probes (i) single point United Sensor sampling probe and (ii) multi-point uncooled sampling probe. General views of the two probe types are shown in Figure 3.2.

Fuel parameters measured were (a) fuel pressure, (b) fuel temperature, and (c) fuel flow rate.

3.2 Water Model Facility

A schematic of the water tunnel installation is shown in Figure 3.3, and a photograph of the installation is seen in Figure 3.4. Plexiglass models of the combustors and casing were suspended vertically in the water tunnel. The tunnel (Figure 3.4) can accept two or three dimensional models of sizes up to 26" x 18" x 18". Quartz strip lighting with a slit arrangement mounted on a travelling frame, enables a light plane to be projected from any side for required viewing. A photographic light source, with a duration of approximately 20 micro-seconds and synchronized with camera shutter, was used to obtain still pictures. A Polaroid camera with type 3000 film was used for photography.

The flow paths in the combustors were traced with polystyrene pellets, aluminum, and colored dyes. The reference velocity in the annulus between the combustor model and the casing was regulated with a flow control valve downstream of the circulating water pump.

3.3 Emission Instrumentation – UACL

For the UB phase of atmospheric development, the following emission measuring instrumentation was employed -

Carle 8000 Basic Chromatograph for CO_2, CO and O_2,
Carle 9000 Flame Ionization Detector for UHC, and
Environmetrics Faristor Detector for NO and NO_2.

For the A/Mod phase of atmospheric development the following instrumentation was used (Figure 3.5) -

Beckman NDIR 315 BL analyzer for CO,
Beckman NDIR 315 B analyzer for CO_2,
Scott Chemiluminescence analyzer with switchable converter for NO_x,
Scott Paramagnetic Analyzer for O_2, and
Carle 9000 Flame Ionization Detector for UHC.

Electrically heated sampling lines providing for gas temperature of about 300 °F were used for sampling. Both single point and multi-point sampling probes were used in the program (see Figure 3.2).

3.4 Pressure Test Facility — UARL

A pressure test facility was developed to provide for air flow rates in excess of 2.25 lbs/sec, pressures up to 250 psia and temperatures as high as 1350 °F. Other auxiliaries included a water cooled instrumentation section, multi-point and single point sampling systems, and facility for humidity variation.

A schematic diagram of the combustor test assembly is shown in Figure 3.6. Probes capable of radial, axial and circumferential traverses were located in the instrumentation section to facilitate pitot pressure and species sampling in the combustor exhaust.

In addition, provisions were made for axial probing of the combustor primary and secondary zones, during selected tests. To take into account possible stratification of pollutants, a multi-point gas sampling probe capable of either collecting six individual radial samples, or a single averaged sample was designed and fabricated. This probe shown schematically in Figure 3.7, was designed for equal area sampling and could be used to obtain detailed radial and circumferential emission distribution.

3.5 Emission Instrumentation — UARL

The emission sampling and analysis system is shown schematically in Figure 3.8. It is capable of continuously monitoring emissions of carbon monoxide, carbon dioxide, unburned hydrocarbons, and oxides of nitrogen. The sample was transferred from the probe to the analytical instruments through 1/4-in. ID stainless steel lines which were wrapped with electrical heating tape and maintained at an average temperature of 400 °F. The sample line length was approximately 50 ft., and the sample temperature was monitored at several axial locations. The emissions analysis system consisted of the following gas analyzers:

1. A Beckman Model 315B long path (41 in. cell) nondispersive infrared analyzer (NDIR) for measurements of Carbon Monoxide (CO) concentrations.

2. A Beckman Model 315B short path (13.5 in. cell) nondispersive infrared analyzer (NDIR) for measurements of Carbon Dioxide (CO_2) concentrations.

3. A Beckman Model 402 Total Hydrocarbon Analyzer which is equipped with a heated Flame Ionization Detector (FID) for measurements of concentrations of Unburned Hydrocarbons (UHC).

4. A TECO Model 10A chemiluminescence detector for measurements of concentrations of Oxides of Nitrogen (NO_x). This unit is equipped with a switchable converter so that total concentrations of NO plus NO_2 may be measured.

Gas mixtures having compositions known to within one percent of specifications were used for calibration.

3.6 Analytical Model — UARL

A computerized analytical model for estimation of the rates of NO_x formation was optimized for use with Class UB and A/Mod type combustors. Results from the model were intended to provide guidance and support in the low emission development of the combustors.

The analytical model is based on a division of the combustor flow field into two zones (Figure 3.9). The primary zone consists of a central recirculation zone (Region I) and an outer stream tube (Region II), and occupies the combustor volume upstream of the first dilution hole. The secondary zone (Region III) comprises the remainder of the combustor. The computer program based upon this model incorporates (1) a fuel droplet vaporization model which serves to determine the local fuel air ratio, (2) an empirical correlation with which the size and shape of the recirculation zone can be established, (3) an equilibrium hydrocarbon thermochemistry routine, and (4) a six-reaction kinetic mechanism - Table 3.1, which represents the NO_x formation processes.

The calculation of internal flows between regions is an iterative procedure which requires input quantities describing combustor geometry, inlet air temperature, chamber pressure, and flow rates through air holes. It is assumed that the unreacted air enters the recirculation zone (Region I) only by entrainment from the combustion air jets at the downstream boundary of the primary zone. The fraction of air that enters the recirculation zone is determined from an empirical correlation given in Ref (8). The remainder of the combustion air enters the secondary zone directly. An additional quantity of air and combustion products enters Region I from Region II. It is assumed that the quantity of air transferred from Region II to Region I is equal in magnitude to the recirculation flow from the primary zone holes.

TABLE 3-1 NITRIC OXIDE FORMATION KINETICS

1.	$O + N_2 = NO + N$	$k_f = 1.4 \times 10^{14} \exp(-37900/T)$
2.	$N + O_2 = NO + O$	$k_f = 6.4 \times 10^{9} T \exp(-3140/T)$
3.	$N + OH = NO + H$	$k_f = 4.0 \times 10^{13}$
4.	$N_2O + H = N_2 + OH$	$k_f = 3.0 \times 10^{13} \exp(-5420/T)$
5.	$N_2O \times O = NO + NO$	$k_f = 2.5 \times 10^{13} \exp(-13540/T)$
6.	$N_2O + O = N_2 + O_2$	$k_f = 3.6 \times 10^{13} \exp(-13540/T)$

Units: T = degrees Kelvin

$$k = \frac{cm^3}{\text{mole-sec}}$$

FIGURE 3.1 CROSS SECTION OF CLASS UB COMBUSTOR ASSEMBLY

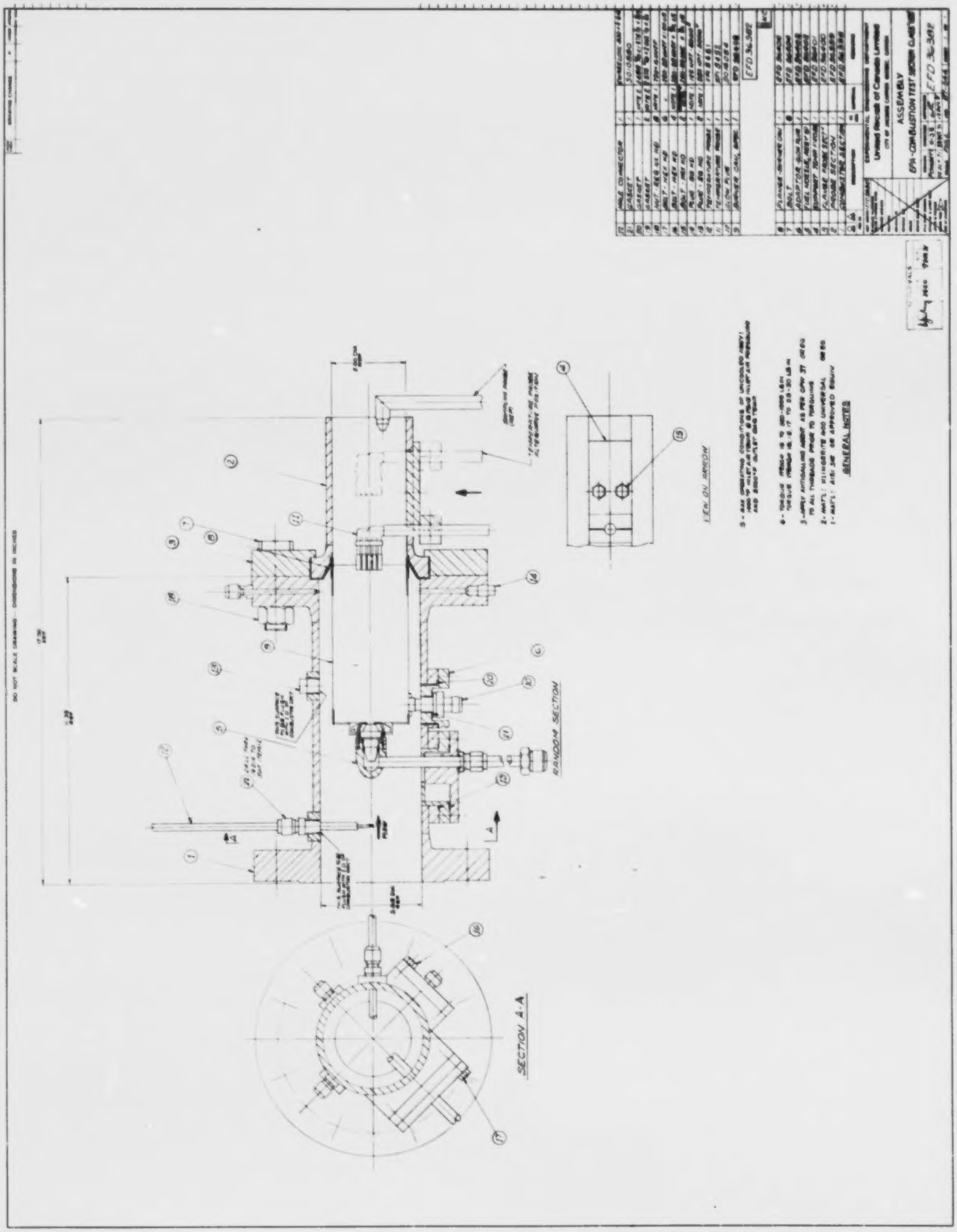

SECTION A-A
RANDOM SECTION
VIEW ON ARROW
GENERAL NOTES
ASSEMBLY
EFD 36302

FIGURE 3.2 SAMPLING PROBES (ATMOSPHERIC TESTS AT UACL)

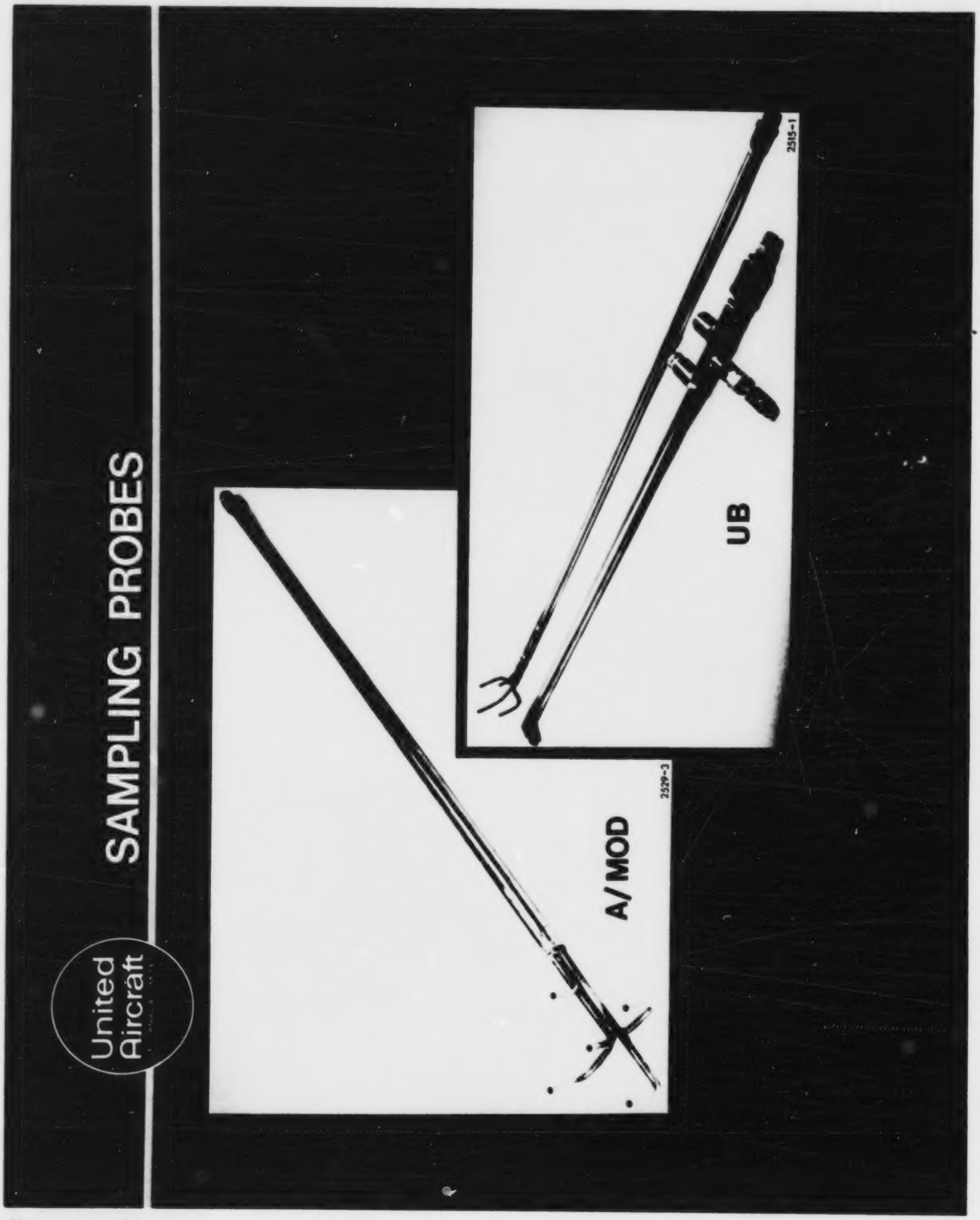

SAMPLING PROBES
United Aircraft
UB
2515-1
A/MOD
2529-3

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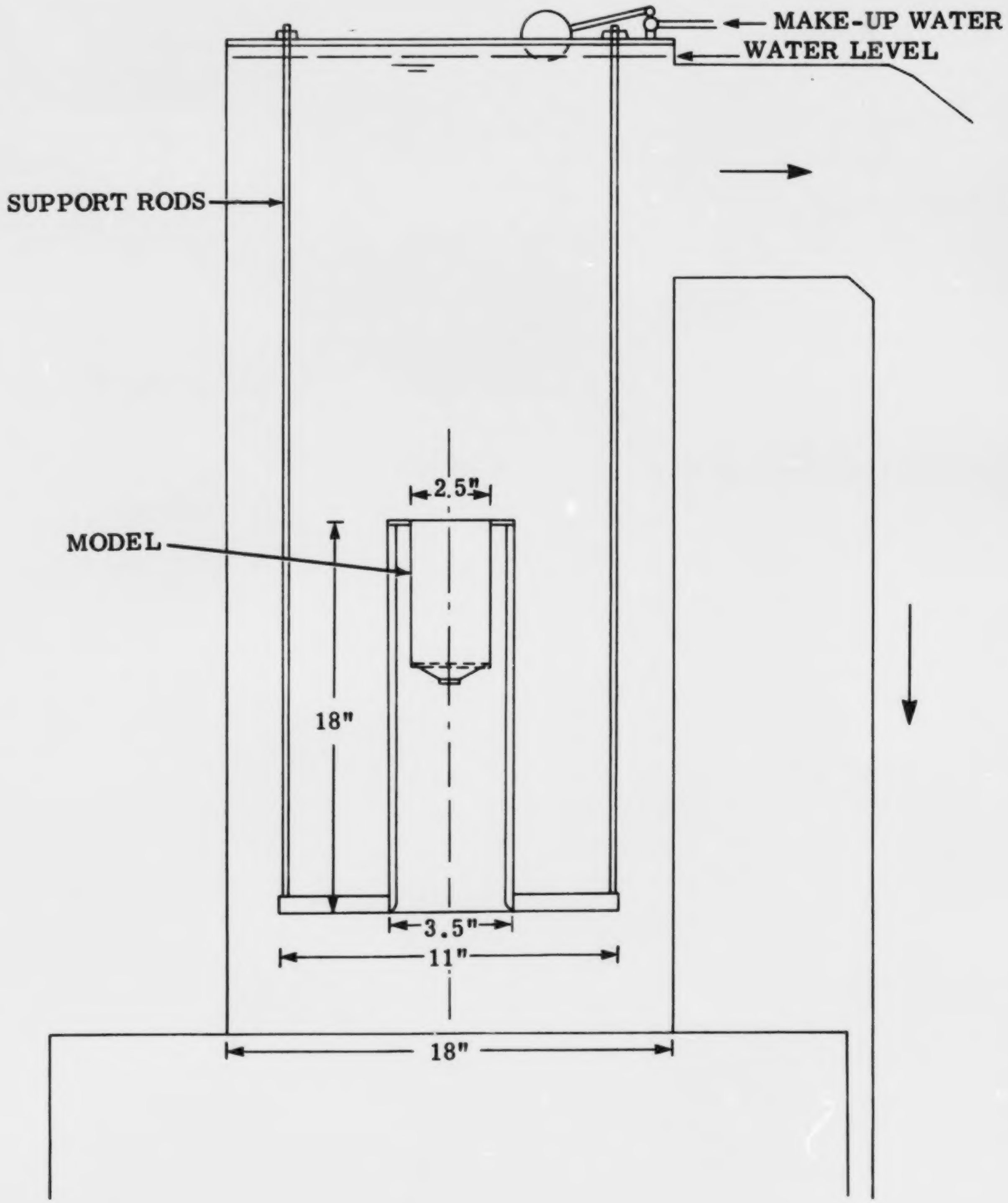
FIGURE 3.3 SCHEMATIC OF THE WATER TUNNEL INSTALLATION


MAKE-UP WATER
WATER LEVEL
SUPPORT RODS
MODEL
2.5"
18"
3.5"
11"
18"

Preceding page blank

FIGURE 3.4 WATER ANALOGY RIG

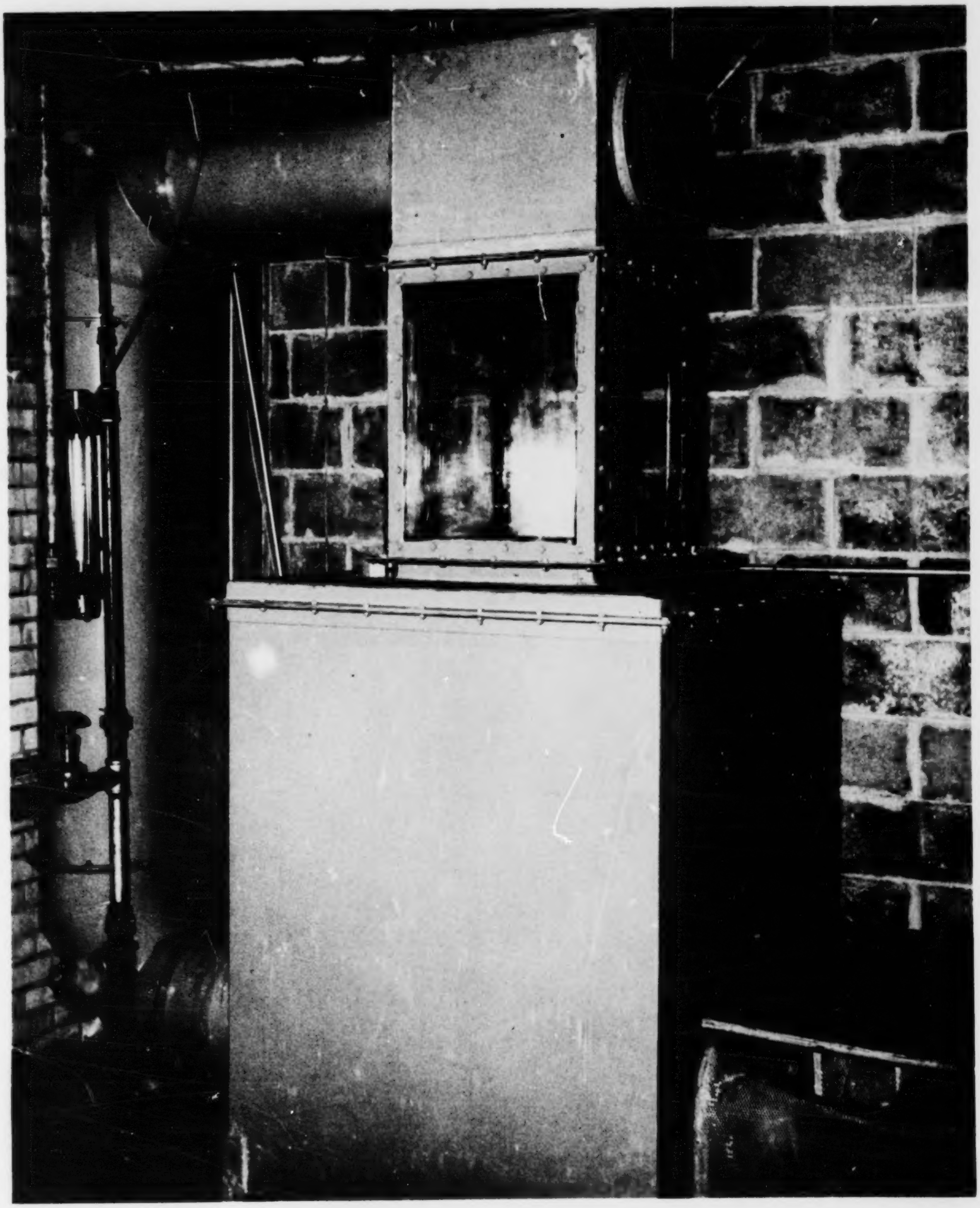


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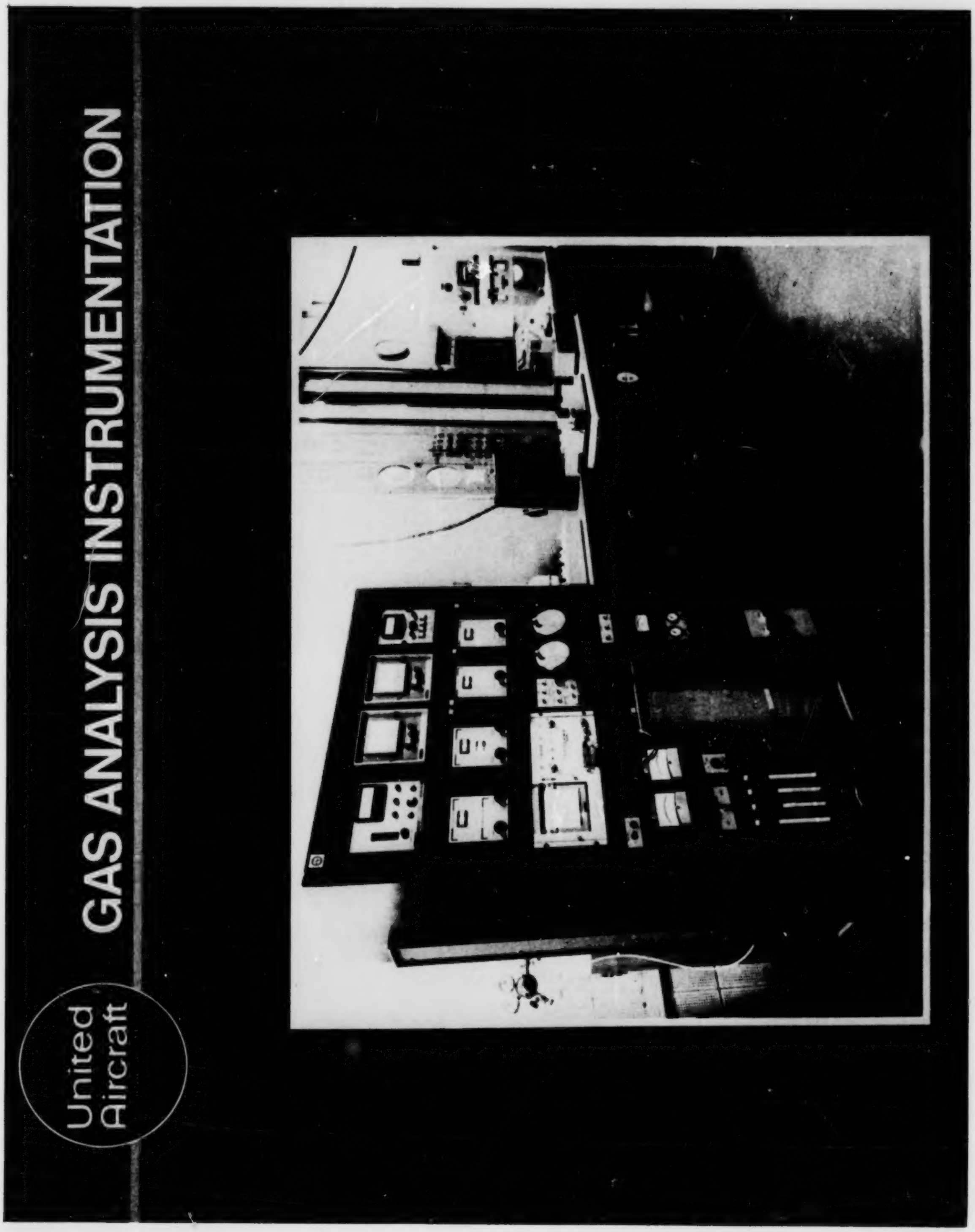
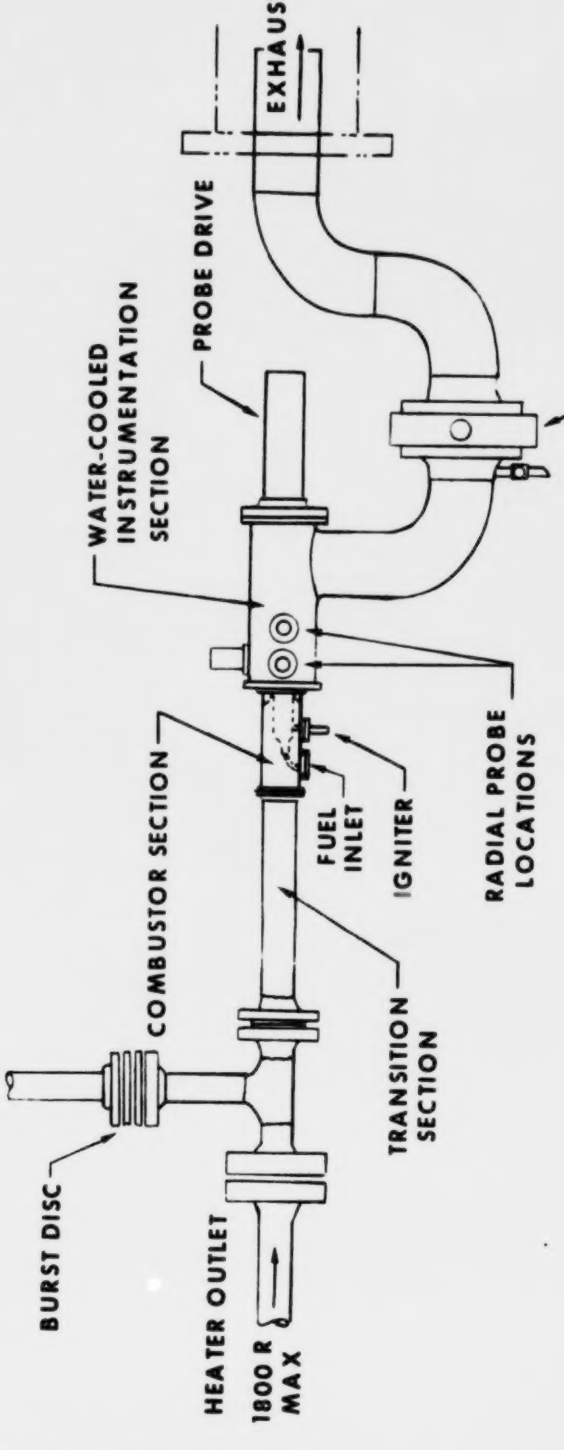
FIGURE 3.5 GAS ANALYSIS INSTRUMENTATION
(ATMOSPHERIC TESTS AT UACL)


GAS ANALYSIS INSTRUMENTATION
United Aircraft

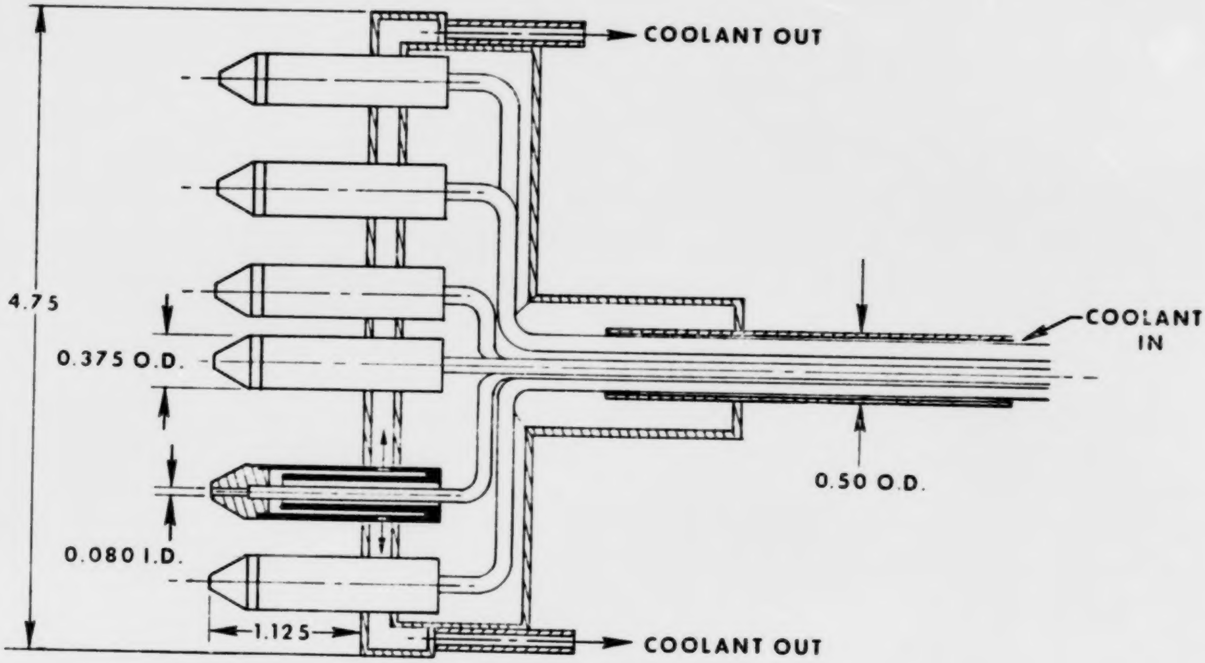
Preceding page blank

FIGURE 3.6 SCHEMATIC OF COMBUSTOR ASSEMBLY (FULL PRESSURE TESTS AT UARL)


EXHAUST
PROBE DRIVE
WATER-COOLED THROTTLING VALVE
WATER-COOLED INSTRUMENTATION SECTION
RADIAL PROBE LOCATIONS
COMBUSTOR SECTION
FUEL INLET
IGNITER
TRANSITION SECTION
BURST DISC
HEATER OUTLET
1800 R MAX

Preceding page blank

FIGURE 3.7 MULTIPOINT SAMPLING PROBE
(FULL PRESSURE TESTS AT UARL)


COOLANT OUT
4.75
0.375 O.D.
COOLANT IN
0.50 O.D.
0.080 I.D.
1.125
COOLANT OUT

Preceding page blank

FIGURE 3.8 EMISSION SAMPLING AND ANALYSIS SYSTEM (FULL PRESSURE TESTS AT UARL)

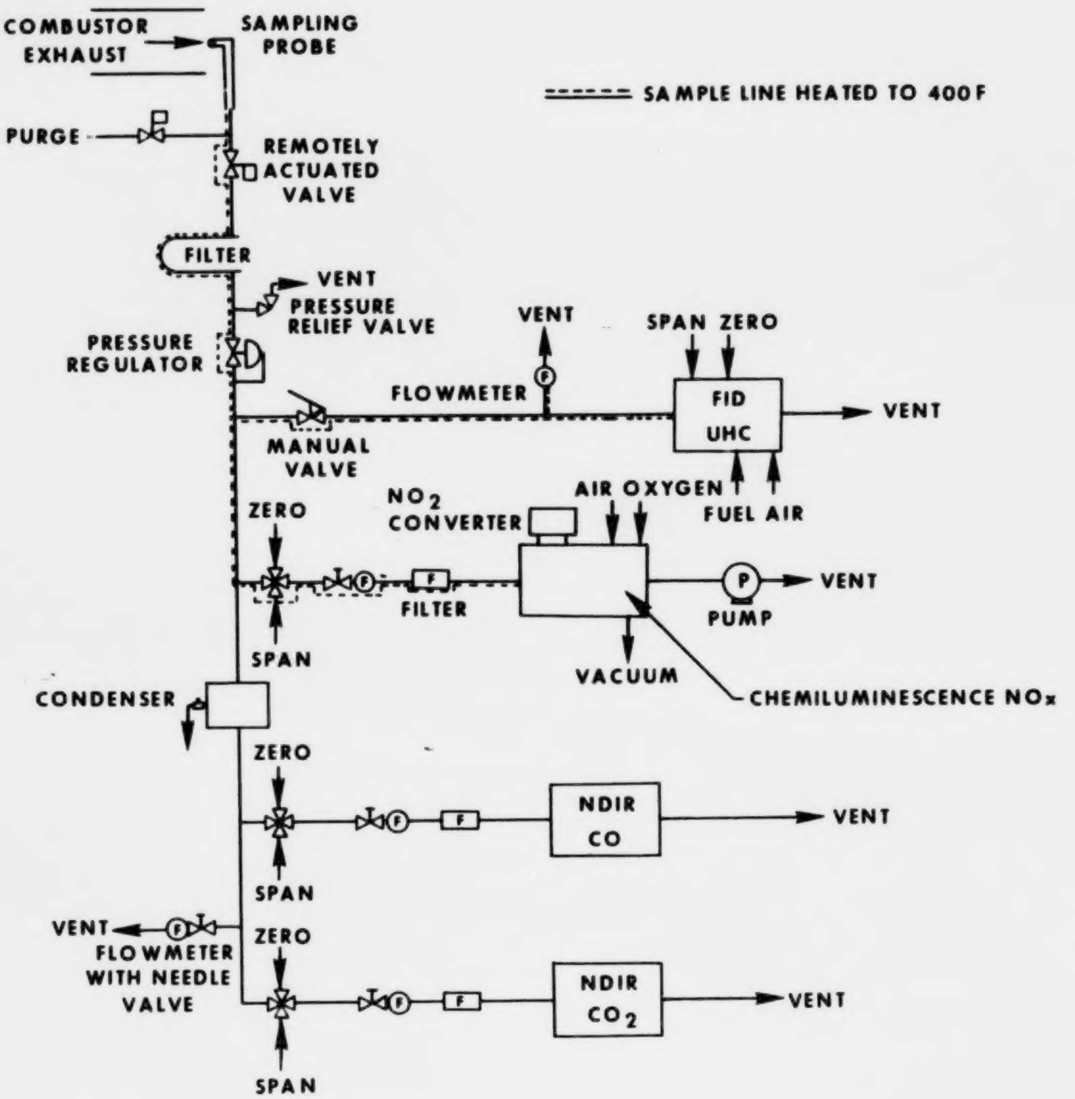

COMBUSTOR EXHAUST
SAMPLING PROBE
SAMPLE LINE HEATED TO 400 F
PURGE
REMOTELY ACTUATED VALVE
FILTER
VENT
PRESSURE RELIEF VALVE
PRESSURE REGULATOR
VENT
SPAN
ZERO
FLOWMETER
FID
UHC
VENT
MANUAL VALVE
AIR
OXYGEN
FUEL
AIR
ZERO
NO_2 CONVERTER
P
VENT
FILTER
PUMP
SPAN
VACUUM
CHEMILUMINESCENCE NO_x
CONDENSER
ZERO
NDIR CO
VENT
SPAN
VENT
ZERO
FLOWMETER WITH NEEDLE VALVE
NDIR CO_2
VENT
SPAN

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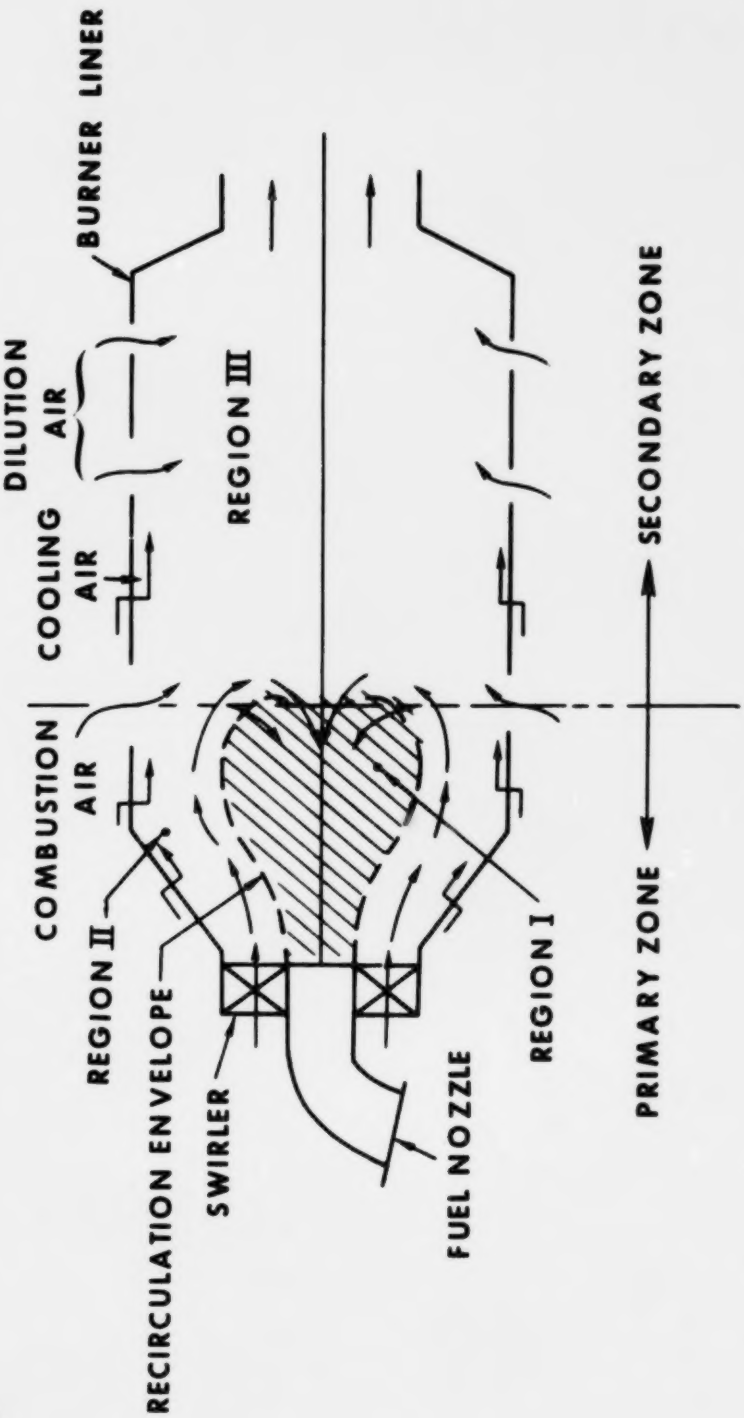
FIGURE 3.9 GAS TURBINE COMBUSTOR FLOWFIELD MODEL


BURNER LINER
DILUTION AIR
REGION III
COOLING AIR
COMBUSTION AIR
REGION II
RECIRCULATION ENVELOPE
SWIRLER
FUEL NOZZLE
REGION I
PRIMARY ZONE
SECONDARY ZONE

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4. DESCRIPTION OF WORK

The development of the two combustors started from flame tube designs based on best known aircraft combustor practices. A brief description of the design considerations, followed by a discussion of the emissions development, is given in the following Sections.

4.1 Class UB Combustor for Simple Cycle Gas Turbine Engines

The Class UB Combustor was designed to parameters representative of the simple cycle (non-regenerated) single shaft, high-pressure ratio (12:1), engine (UAC SSS-12). The combustor design conditions, as specified by EPA, are -

Heating rate = 1.5 x 10^6 BTU/hr
Inlet air temperature = 800°F = 1260°R
Inlet air pressure = 12.0 atm = 176.4 psia
Overall fuel-air ratio = 0.0195
Fuel flow (JP4) = 77 lbs/hr
Air flow = 4000 lbs/hr = 1.11 lbs/sec.
Outlet temperature = 1900°F = 2360°R.

4.1.1 Combustor Volume

Since at the design point the pressure is above 4 atmospheres, Tipler's relationship(7) can be used -

$$\frac{W_f}{PD^2} = C\sqrt{T\,\frac{\Delta P}{P}} \;;\; C = \frac{W_f}{PD^2}\sqrt{\frac{P}{\Delta P \times T}}$$

As a design basis, values of C used in other engines with Can Combustors were considered. A pressure loss $\frac{\Delta P}{P}$ = 2.5% was used for design purposes.

A value of C = 0.210 was considered reasonable. This leads to

$$C = 0.210 = \frac{77}{12 \times D^2 \sqrt{1260}}\sqrt{\frac{100}{2.5}}$$

or D = 2.4 inches.

The lengths were chosen on the basis of:

Primary Zone = $\frac{D}{2}$ = 1.3 ins. (say), to provide for a double vortex recirculation.

Intermediate Zone, based on an approximate empirical rule, $\frac{L}{D}$ = 5/8

Intermediate Zone Length = 1.6 ins.

Dilution Zone length chosen to provide for good mixing length and even temperature distribution. Dilution Zone Length = 2.5 inches.

Overall length of the combustor = 5.6 inches.

It was realized that the lengths of the three combustor zones would have to be finally determined by analysis of air flow distributions and consideration of residence times and emissions from the combustor. In fact, during development of the combustor for low emissions, an increase in overall combustion length to 7.0 inches was found to be beneficial.

A summary of design data for the Class UB Combustor is given in Table 4-1.

4.1.2 Water Model Studies - Class UB Combustor

The development of flow paths in the combustor was complemented by water analogy studies, where aluminum dust and polystyrene tracers were used to observe flow paths. Attempts were also made on the water analogy rig to measure the speed of tracers and hence residence times. Some details of the water analogy studies are given in the Appendix A. Figure 4.1 shows a cross section of the Class UB water model. The water model was found to be a very useful tool in establishing flow paths and flow splits. However, estimates of residence times obtained from the water analogy studies are at best indicative of trends and ranges.

NO_x being the prime pollutant of concern, some control criteria were considered during the design of the combustors. Three factors are considered important in the formation of NO_x in gas turbine combustors: (a) temperature (both of combustion reaction zone and intermediate zone), (b) residence time of hot post-flame gas, and (c) excess oxygen. Reaction zone temperatures are a maximum for an equivalence ratio of homogeneous reacting mixtures about 0.9-0.95. Combustion of very rich or very lean mixtures can result in lower primary zone temperatures. It was felt that going to a lean primary zone would be preferable since CO can be oxidized at temperatures at which NO_x formation rates are low. Although the primary zone was initially designed for an average equivalence ratio of 0.95 at design point mainly to establish a baseline, development for low NO_x would try reducing ϕ_{PZ}. CO could be controlled by maintaining the intermediate zone between 2000 and 2500°F where the NO_x formation rate is low.

To provide for good mixing in the primary zone and to improve the stability, a swirler was incorporated. Plunged holes in the dilution zone were expected to improve quenching, if required. The flow paths with the swirler in the head end and plunged holes in both primary and dilution zones, were evaluated on the water analogy rig.

4.1.3 Atmospheric Rig Development - Class UB Combustor

Atmospheric development on the combustor was done on the test facility at UACL. To start with, a pressure jet atomizer with a Flow Number (defined as the ratio of fuel flow rate in lbs per hour to the square root of the pressure drop across the injector in lbs/per square inch) of approximately 1.0 was used. Emission measurements followed initial modifications to the combustor aimed toward maintaining a stable flame over the operating range on the simulated Federal Driving Cycle (FDC) (Table 4-2). To simulate the operating conditions on FDC atmospherically, the ratio $\frac{W_{in} \sqrt{T_{in}}}{P_{in}}$ was kept constant for each of the operating points. During development for reducing emissions, only conditions corresponding to FDC #2 (Table 4-2) were simulated since this represented 76% of the simulated Federal Driving Cycle. At the same time the lean limit characteristic of the combustor was monitored so that the combustor modifications to reduce emissions would not conflict with the requirements of maintaining a stable flame over the entire operating range of the engine.

Figure 4.2 summarizes the milestones in Class UB combustor development, at atmosphere pressure. Shown herein are the Emissions Index for Oxides of Nitrogen (expressed as E I NO_2), equivalence ratio in the primary zone (ϕ_{pz}) computed on an average basis and combustor pressure drop ($\Delta P/P_{in}$). The first version of the combustor had smaller holes than designed for, since it was desired to increase hole areas gradually. Hence the high pressure drop (7.1%). The first step was to bring the pressure drop to more reasonable levels, which was done by a proportional increase in hole areas in all regions of the combustor. Reducing the can pressure drop from 7.1% to 5.15% raised the NO_x Emissions Index from 2.1 to 2.25 - reflecting the effect of reduced penetration through mixing holes. Effect on CO and UHC emissions was minimal. Next, increased quench while maintaining reasonably constant levels of primary zone equivalence ratio and combustor pressure drop was tried. This was done by shifting some of the dilution air into the intermediate zone. The result was a substantial decrease in NO_x levels to values below those measured on the 7.1% pressure loss combustor (Figure 4.2). There was a substantial increase in CO levels, which was thought to be due to the lower temperatures in the intermediate zone. The increase in UHC emissions with these modifications was quite minimal. Modifications aimed at leaning of the primary zone were attempted by a combination of enlarging the hole areas in the primary zone, and shifting the primary zone plane of holes upstream. The result was a leaner primary zone, a lower combustor pressure loss (Figure 4.2) and a slightly worse lean blow out limit. The NO_x emission index reached levels at the maximum weighted condition (FDC #2), close to targets for the integrated Federal Driving Cycle. The pressure loss was close to the target (2.5%) and ϕ_{pz} was about 0.53. The CO levels with these modifications were well above target, but were expected to be substantially lowered under actual pressure operating conditions. It was becoming obvious, however, that further leaning of the primary zone would seriously affect the lean-end performance - under atmospheric pressure conditions. No concrete information was available on the effect of pressure on CO emissions, thus rendering difficult optimization of combustor for low NO_x and CO emissions at the same time. It was therefore decided to continue further development under full pressure conditions.

Effect of air-assist and air-blast nozzles on NO_x emissions was also evaluated. The three types of atomizers are shown schematically in Figure 4.3 and a photograph is also included (Figure 4.4). All three were developed by Delavan Manufacturing Company. Emissions of NO_x were slightly higher with the air-blast nozzle than with the air-assist nozzle, (Figure 4.2). No direct comparison with pressure atomizers was possible, since the head end geometry and hole pattern had to be altered significantly to accomodate it. UHC emission with the air-assist nozzle was significantly better and only marginal differences in CO levels were measured. No modifications either to the swirlers with air assist/air blast nozzles or to the head end swirler were evaluated on the low pressure rig.

The variation of NO_x emissions with overall fuel-air ratio at inlet temperatures and air flow corresponding to the maximum weighted condition on the simulated Federal Driving Cycle is shown in Figure 4.5. The three curves correspond to: (1) One of the early versions of the combustor, with a combustor pressure loss approximately 5%; (2) An early quench combustor; and (3) A combustor incorporating both the early quench and lean primary zone approaches. The reductions in NO_x levels accomplished by these modifications is evident, Figure 4.5.

The Combustor geometry and mixture conditions corresponding to the three above situations are shown in Figures 4.6, 4.7 and 4.8. At the lowest point on the Federal Driving Cycle (FDC #1), the equivalence ratio (based on calculations) would be 0.14 (Figure 4.8) and it was no surprise that a satisfactory flame could not be maintained atmospherically at this condition.

The variation of NO_x emissions with overall fuel-air ratio appears to be significantly influenced by the primary zone mixture conditions. For example, with a combustor having a lean primary zone with early quench, the NO_x emission indices (Figure 4.8) decrease with increase in overall fuel-air ratio whereas with conventional combustors ($\phi_{PZ} \approx 0.9$ approx.), the trend is reversed (Figure 4.6). These effects suggest the strong influence of primary zone aerodynamics on emissions. Some of the conclusions from the class UB atmospheric development are -

(1) Atmospheric development of the combustor showed that substantial reductions in NO_x emission levels could be accomplished rapidly.

(2) Interpretation of emission levels rely on good estimates of the effect of full pressure on emissions. While some analytical estimates were made for NO_x using the Kinetic Model, the effect of pressure on CO,

UHC and lean limit could only be guessed, as no models for these were available. Thus, the emissions can only be interpreted on a qualitative basis.

(3) The apparently strong influence of pressure in improving the lean blowout characteristics, limits the extent to which the head end of the combustor can be leaned out at atmospheric pressure for purposes of reducing NO_x emissions.

4.1.4 Class UB Analytical Modeling

As reported previously, the analytical model for estimating the rates of NO_x formation in gas turbine combustors (8) was expanded to permit the use of the recirculation zone geometry and air entrainment rates determined by water flow visualization studies (Section 4.1.2). A series of calculations was carried out by UARL to check the revised combustor flow field model and to predict the level of NO_x emissions for the Class UB combustor. Combustor operating conditions, geometry and airflow chosen for analysis are summarized in Tables 4-4 and 4-5. The results shown in Figure 4.11 indicate that, for combustor geometries which engendered a lean and uniformly mixed primary zone and rapid quenching of the combustion products, the predicted level of NO_x emissions are encouragingly low. It should be noted, however, that the analytical predictions are based on the assumption of uniform mixing in each of the three regions of the combustor (i.e. the central recirculation zone, the contiguous stream tubes, and the secondary zone) and therefore indicate trends and goals which may or may not be realized in actual combustor testing. In this regard, a calibration of the analytical model was undertaken using experimental data compiled during atmospheric testing of the combustor. These data corresponded to an initial combustor configuration which utilized a conventional pressure-atomizing fuel nozzle and was designed for primary zone fuel-air ratios approaching stoichiometric. The model calibration was accomplished by incorporating the results of water flow visualization studies and by suitably modifying the primary zone fuel-air ratio to more accurately represent the mixture non-uniformities which are characteristic of a pressure-atomizing fuel nozzle. Figure 4.12 presents a comparison of the measured NO_x emissions versus the NO_x emissions predicted by the calibrated water model. The theoretical predictions shown are based on the assumption that combustion in the primary zone occurs at a stoichiometric mixture ratio. The results shown indicate good agreement between the experimental data and the theoretical predictions.

Cross plots of NO_x emissions with equivalence ratio and residence time were made for a mixture inlet temperature of 425°F corresponding to the maximum weighted condition on the simulated Federal Driving Cycle (Figure 4.13). Although uniform mixing was a pre-condition in these calculations, the curves served as a useful guide in the UB development program.

The analytical model for estimation of the rates of NO_x formation in gas turbine combustors was also used to evaluate the effect of inlet air pressure and humidity on the level of NO_x emissions for the simple-cycle combustor. The information was particularly useful since it provided a basis for comparison of low pressure (atmospheric) emission data obtained at UACL with the pressure data obtained at UARL. The analytical predictions were carried out for a range of primary zone fuel-air ratios and at inlet conditions corresponding to the maximum weighted point on the simulated Federal Driving Cycle. The results presented in Figure 4.14 indicate that NO_x emissions increase by a factor of approximately 2.5 as the combustor operating pressure (P_{in}) is increased from 15.26 to 61 psia.

The effects of inlet air humidity on combustion zone temperature and on NO_x emissions were investigated from the analytical model. The results shown in Figure 4.15 indicate that NO_x emissions are reduced as the moisture content of the inlet air is increased. For example, in a combustor operating with a primary zone fuel-air ratio near stoichiometric, combustion in air with a humidity of 0.010 lbs H_2O/lb air (50% relative humidity at 76°F) will produce twenty-five percent lower NO_x emissions than combustion in dry air. For leaner primary zone fuel-air ratios, the reduction will be greater. However, mixture non-uniformities may reduce this effect under actual combustor operating conditions.

CO modelling has been based completely on equilibrium thermochemistry. Figure 4.16 shows the variation of equilibrium combustion temperature with fuel-air ratio, for inlet conditions corresponding to the maximum weighted point on the simulated Federal Driving Cycle. Figure 4.17 shows variation of CO mole fraction at equilibrium with overall fuel-air ratio for inlet conditions corresponding to the two heavily weighted Federal Driving Cycle points (FDC #2 and FDC #3). The actual CO concentrations would however depend on the local temperatures, degree of homigeneity in the reaction zone, droplet-size and local quenching effects.

4.1.5 Class UB Pressure Development

This phase of the program was undertaken at United Aircraft Research Laboratories, under personal supervision by UACL staff. A brief description of the UARL pressure facility was given in Chapter 3. All developmental testing was done with dry, unvitiated air at conditions corresponding to the simulated Federal Driving Cycle. During investigations on humidity effects, the moisture in the inlet air was carefully monitored and controlled.

The limitations of atmospheric testing, i.e., the poor stability with lean head end configuration, forced a change of plans to allow more development testing at full pressure. Plans to do detailed multi-point and axial sampling were therefore scrapped and emissions were monitored through a five-point traverse with a single-point air-cooled sampling probe. The multipoint probe was replaced with a sight glass allowing full on-axis viewing of the combustor. This proved to be an important technique as the majority of unintended combustion changes due to fuel or air inlet asymmetries could be spotted as flame asymmetries, streaks or spottiness. Flame locations, colors, brightness and stability also rendered a qualitative understanding of flame properties as they related to emissions. More than two hundred modifications were evaluated and a number of these were re-tested due to visual evidence of rig, combustor or fuel injection mechanical troubles. The facility to visually observe the flame enabled emission data to be more easily understood. A compilation of combustor configurations and test results is given in Appendix B.

Combustor development in the pressure facility started by evaluation of emissions on the final combustor configuration resulting from atmospheric development program (Figure 4.9). This combustor was evaluated on the simulated FDC with (1) pressure atomizer with Flow Number approximately 1.0, (2) air-assist atomizer Flow Number approximately 1.0, and (3) air-blast atomizer with flow number approximately 3.5. Some specifications on these fuel nozzles are given in Appendix B-5. The results, shown in Figure 4.18, indicate that air-assist and air-blast fuel nozzles contribute to less NO_x and CO emissions compared with the pressure atomizer. The air-blast atomizer produced slightly more UHC emissions than the pressure atomizer and significantly worse than the air-assist nozzle. This may be the effect of poor performance of the air-blast at low fuel flows where the momentum of the fuel is small. This aspect of air-blast atomization is discussed in Section 5.3.

Direct comparison of atmospheric and pressure test data showed that NO_x levels at full pressure increased by 160%, while CO and UHC emissions decreased by 74% and 72% respectively, over the atmospheric emission levels. However, correcting both sets of test data to standard humidity conditions (55% relative humidity at 76°F) results in apparent increases in NO_x due to pressure alone of 125 to 150%. This compares favorably with the 150% increase expected from the analytical model.

It became clear, early in the full pressure development program, that the problem area is the inverse (not always linear) relationship between the NO_x and CO emission indices. The UHC increase accompanying reduction in NO_x levels appeared in most cases to be a second order effect. It was therefore decided to correlate the emission indices of NO_x and CO for the various combustor modifications attempted. The air-assist fuel nozzle was the initial choice in view of its apparently better performance over the pressure atomizer and lower UHC compared to the air-blast atomizer. Figure 4.19 shows EI_{NO_2} vs EI_{CO} relationships for an air-assist nozzle over a variety of combustor configurations. The emission data, refer to FDC #2 and 3, which are the heavily weighted conditions on the simulated Federal Driving Cycle (Table 4-2), the UHC levels were at or below target for all but damaged hardware. For obvious reasons, the damaged hardware data could not be reproduced. The upper curve refers to all combustor modifications excepting the ones involving the head end swirler. Irrespective of the approaches tried - rich/lean primary zone, low/high pressure drop, early/delayed flame quench - the data conformed to the band represented by the top curve. The bottom curve refers to air-assist nozzle data with an additional swirler in the head end, in the same direction as can swirler. The data points in this case fall on a curve which appeared to approach the target levels. This breakthrough in the trends was considered a milestone in the Class UB combustor development program.

The effect of the additional swirler in bettering emissions, was thought to be due to improved mixing in the primary zone. Qualitatively, the high swirl flame appeared more uniform and there was also an improvement in the lean blow-out limit.

Some attempt was made to repeat the damaged hardware data shown in Figure 4.19, but the combustor had been through so many modifications - some of them of a 'quick fix' nature - that a new flame tube was the only way to get back to those conditions. Since there were other avenues planned for investigation, further attempts to get back to the data points close to the targets were abandoned.

On-axis viewing of the flame showed that in the case of lean front end combustor with an air-assist fuel nozzle, a rich core - typified by an orange flame - existed in the primary zone at all conditions. Also, the low Flow Number of the air-assist fuel nozzle used rendered it susceptible to contamination , usually only evident by on-axis viewing of the flame, and requiring frequent replacing of the fuel nozzle 'guts'. It was therefore decided to try the air-blast nozzle which operated on a much lower fuel pressure drop and was less likely to develop streaks in spray, because of the dominant effect of air momentum.

Figure 4-20 shows variation of Emission Indices of Oxides of Nitrogen and Carbon Monoxide for the case of air-blast atomizer used in conjunction with a high primary swirl combustor. Also shown for comparison are the air-assist data. While the slope of the EI_{NO_2} vs EICO curve is steeper, and very sensitive to the combustor geometry, the emission data were extremely repetitive. The high swirl in the primary zone rendered the flame stable, symmetrical and highly homogeneous. The rich core so apparent with pressure and air-assist fuel nozzles was not present with this arrangement of air blast nozzle. At the closest point, the NO_x emissions integrated over 96% of the simulated Federal Driving Cycle were about 29% over target and CO emissions 19% below target. The establishment of this working line for air-blast with the repeatability of data - so important in combustor development for low emissions - was considered another milestone during the Class UB development program.

It became apparent that with an extension of the high swirl approach, in conjunction with a suitable air-blast nozzle, a working line could be established which at its closest point was well within the 1976 targets. However, such an effort could not be undertaken due to lack of funds for this phase of the program. Hence, the Class UB development was concluded by choosing a combustor configuration which was close to target (Figure 4. 20) and undertaking complete evaluation on the simulated Federal Driving Cycle, Steady Speed and Range Mode operations. These data are presented in a following Section.

4.1.6 Effect of Atmospheric Moisture on Exhaust Emissions - Class UB Combustor

To establish the true levels of exhaust emissions, it is important to know how ambient air conditions affect the emissions. This became clear during the atmospheric phase of development on the Class UB Combustor, when no humidity control was incorporated in the rig. During pressure development at UARL the air from the compressor was dried and a careful check of the moisture in the inlet air was maintained (Dew Point below -40°F).

Water vapor has been established to have a significant effect on Nitric Oxide emissions and therefore steam injection is often a considered possibility toward reduction of Nitrogen Oxides from stationery power sources. (9, 10)

The weight fraction of water in dry air for varying conditions of dry bulb temperature and relative humidity are readily found from psychometric charts. On hot, humid days 2% and even 3% by weight of water vapor may be present in the atmosphere.

Another way of expressing moisture content of ambient air is as "grains" of moisture per pound of dry air. There are 7000 grains in a pound. Table (4-6) relates the various terms for expressing moisture content.

Specification for ambient air moisture (specified in the Federal Register (1)) was with reference to piston engine exhaust emissions. These call for emissions to be related to an absolute humidity of 75 grains of moisture per pound of dry air which corresponds to 1.07% of water vapor by weight or a relative humidity of 55% at 76°F.

The importance of atmosphere moisture on Nitric Oxide formation lies in the fact that it reduces the flame temperature, on which the NO_x formation rate is strongly dependent. John Moore (11) analytically determined that each one percent of water vapor reduces the adiabatic flame temperature (of stoichiometric hydrogen-air and ethylene-air mixtures) by approximately 36°F. This temperature reduction combined with the additional water in the flame also reduces the oxygen atom concentration. Moore found a reduction in the rate of nitric oxide production amounting to approximately 25% for each 1% of water vapor.

The calibrated analytical model for Class UB combustor (Section 4.1.4) was used to estimate the effect of inlet air moisture on NO_X emissions. The results, which were referred to earlier (Figure 4.15), show that the effect is also a function of primary zone fuel-air ratio. For a stoichiometric, uniformly mixed primary zone, combustion in air with a humidity of 1.07% by weight of water (75 grains), the NO_X emissions will be twenty-five percent lower than combustion in dry air. For leaner primary zone fuel-air ratios the effect can be even greater.

To verify the above analytical predictions, tests were done on the Class UB combustor monitoring the exhaust emissions as the inlet moisture was varied. Figure 4-23 shows a schematic of the test facility at UARL modified for humidity evaluation. Water was introduced as a fine spray into the hot air stream and sufficient length of ducting was provided for uniform mixture conditions to be established, before the combustor test section. The humidity was monitored with a Dew Point Meter and exhaust emissions were measured only after stable moisture conditions in the inlet air were recorded.

The combustor configuration chosen for the study had a richer primary zone than the final configuration. NO_X reduction therefore could be expected to be less, Figure 4.15 . Figure 4.24 shows a summary of measured NO_X reductions as a function of inlet air moisture. For Class UB conditions (96% of FDC) the percentage NO_X reductions at the standard humidity condition is in the range of 23-24.5%. No significant effects were observed on CO and UHC emissions at this humidity condition.

The estimated fuel-air ratio in the primary zone at the maximum weighted condition on the simulated Federal Driving Cycle was approximately 0.039. For this configuration the analytical model predicted an effect on NO_X mass fraction of about 40% reduction at the standard humidity condition compared to dry air. The experimentally observed effect was 23.5%; the difference could be attributed to the prevalence of non-homogeneous (locally rich) burning conditions in the reaction zone. In the configuration used for final evaluation, the primary zone was generally leaner due to (i) use of the air-blast nozzle and (ii) high swirl improving reaction zone mixing. These modifications may therefore be expected to result in humidity having a greater effect on NO_X emissions, at standard conditions.

Also shown in Figure 4.24 are the humidity effects on NO_X emissions from Class A/Mod Combustor. These results are discussed in detail in Section 4.2.4.

4.1.7 Class UB Combustor Final Evaluation

A combustor configuration, which demonstrated emissions close to targets over 96% of the simulated Federal Driving Cycle (Fig. 4.22), was chosen for final evaluation. This represented Emission Indices 29% above target on NO_X, 18.5% below target on CO and 85.5% below target on UHC. It is believed that these levels could be improved to below target levels for all species by further pursuit of the approaches used - viz., high swirl, air-blast and lean head end.

The final evaluation comprised of measuring emissions and temperature profiles across the combustor exit plane for operating conditions representing (a) simulated Federal Driving Cycle (Table 4-2), (b) Steady Speed Mode (Table 4-7), and (c) Range Mode (Tables 4-9 and 4-10). The simulated Federal Driving Cycle data are presented as integrated emissions (Table 4-12 and Figure 4.25). The Emission Indices for Steady Speed and Range Mode operations are presented in the form of parametric curves (Figures 4.26 to 4.34.) Typical profiles of exit temperature are shown in Appendix B.

Figure 4.25 is a graphical representation of emission indices and emission ratios integrated over 96% (FDC #2 plus FDC #3) and 100% of the simulated Federal Driving Cycle. The 100% figures represent emission values 29% above target on NO_x, 20% above target on UHC and 7% above target on CO. The high fuel-air ratio (0.015) representing FDC #4 (Table 4-2) does not appear to significantly influence the NO_x emissions, while the low fuel-air ratio (0.0052) representing FDC #1 (Table 4-2) has a large effect on CO and UHC emissions. The rather high levels of UHC on FDC #1 which only represents 3% of the simulated Federal Driving Cycle, is thought to be due to operation of the air-blast nozzle below its efficient minimum range. This air-blast nozzle was used because it was available, but it is oversized for this application. This aspect of the air-blast nozzle operation is further discussed in the following Chapter.

The results of emissions evaluation tests conducted on the Class UB combustor at conditions simulating constant vehicle speeds between thirty and ninety miles per hour are summarized in Table 4-8, the data being obtained at zero humidity. The variation of the emissions with vehicle speed, fuel flow and engine SHP are shown in Figures 4.26, 4.27, 4.28 and 4.29. The NO_x emissions in these curves have been corrected to standard humidity by applying the same correction factor previously determined for operation over the simulated FDC. Also shown in Figure 4.28 is the variation of overall equivalence ratio (ϕ). The NO_x and UHC emissions follow expected trends based on increasing pressure, inlet temperature and fuel-air ratio, as the vehicle speed (or power) increases. The CO emissions follow a wavy pattern, which is considered to be the result of varying influences of primary and intermediate zone reactions. The high CO at the 30 MPH (Figures 4.26 and 4.27) condition could be an effect of the lean head end together with relatively low intermediate zone temperatures. As the speed increases to 50 MPH the reduction in CO emission is due to a hotter intermediate zone. The rest of the CO curve is thought to be a reflection of primary zone kinetics (compare with Figure 4.17).

In order to evaluate the significance of changes in inlet air pressure and temperature on the levels of pollutant emissions from the Class UB combustor, a series of tests was conducted at two baseline conditions selected from the combustor design range. The overall fuel-air ratio and the Mach number of the inlet air were held constant while the inlet pressure and temperature were systematically varied.

Figures 4.30 through 4.34 show results of combustor operation on the Range Mode(Tables 4-9 and 4-10). The low base line represents a vehicle speed of 50 MPH, while the medium base line corresponds to a vehicle speed of 70 MPH. Raising of pressure or temperature increases NO_X while reducing CO and UHC. This is primarily a result of the increase in combustion temperature, which rapidly increases the rates of NO formation and CO oxidation. In addition, emissions levels at the high-power operating condition appear to be more sensitive to changes in pressure and temperature than the corresponding levels at the low-power test condition. With a decrease in inlet pressure or temperature the effect is reversed. The Range Mode data is expected to provide background information on emissions for further optimization of engine operating cycles.

Finally, temperature profiles measured in a plane 3.5 in. downstream from the combustor exit are plotted in Appendix B. These data correspond to operation at each of the four points on the simulated Federal Driving Cycle. Calculations based on exhaust gas concentration measurements indicate that the combustor operated at high thermal efficiency throughout the specified cycle. Thus, the Class UB combustor demonstrated acceptable performance in terms of combustion efficiency, combustor pressure drop and exit temperature distribution.

4.2 Class A/Mod Combustor for Regenerative Gas Turbine Engines

Class A/Mod Combustor was designed to parameters representative of the regenerated, low-pressure ratio engine. The combustor design conditions were -

Inlet air temperature = 1100°F = 1560°R
Inlet air pressure = 5.0 atm = 73.4 psia
Overall fuel-air ratio = 0.0124
Fuel flow (JP4) = 67 lbs/hr.
Air flow = 1.5 lbs/sec.
Outlet temperature = 1900°F = 2360°R

4.2.1 Design Philosophy

As a result of the design and water modelling experience on the Class UB combustor and keeping the low NO_X requirements in mind, the following design approach was used for the Class A/Mod combustor:

A basic design deviating slightly from standard aircraft practice, the main differences being:

(a) A primary zone with an equivalence ratio (ϕ_{PZ}) of 0.85 instead of 1.0 - this would be a better starting point for further leaning of the primary zone.

(b) Intermediate zone holes much closer to primary zone to effect early quench of primary zone effluents.

(c) A lower intermediate zone temperature - 2900°R instead of 3250°R - in order to be below the NO_X production temperature and remain high enough to consume CO and hydrocarbons formed in the primary zone (dissociation) reactions. It is generally said that the intermediate zone is a buffer zone which helps attain good efficiency at altitude and is somewhat superfluous for ground level operation. But here the intermediate zone can be very useful as a dwell zone to consume CO and UHC, and if its temperature is low enough, it will not contribute to NO_X formation.

(d) Good fuel atomization and homogeneity of reacting mixtures are essential to ensure uniformly low primary zone temperatures. NO_X production is strongly dependent on temperature, and locally rich pockets would result in higher local temperatures and hence higher NO_X emissions. A swirler in the head end was chosen to provide good mixing in the primary zone, and strong recirculation for combustion stability.

The above guidelines provided a basic design for Class A/Mod combustor. To achieve a $\phi_{PZ} = 0.85$, the air split into the primary zone was set at 21.6%. To set up an intermediate zone temperature of 2900°R calls for a fuel-air ratio (at design point) of 0.0219. The required intermediate zone flow was 16.5%. Assuming a 55% flow from primary zone holes into the intermediate zone and 3% for cooling air, 3% of the total air flow was required through holes in the intermediate zone, to maintain 2900°R intermediate zone temperature. The remaining air (61.9%) was introduced into the dilution zone. Employing sizing techniques similar to those of Class UB combustor, a diameter of 4.0" as chosen for Class A/Mod combustor. The lengths of the individual zones were -

Primary zone (L_{PZ}) = D/2 = 2.0"
Intermediate zone (L_{IZ}) = 5/8D = 2.5"
Dilution zone = 1-3/8D = 5.5"
Total length = 10"

A casing with a diameter of 6" was chosen, providing for an annular velocity of 105 feet/sec.

In the basic design about 6% of the flow was provided through the swirler in the head end, the remaining primary zone air passing through the nozzle sheath (1%), cooling slots (6%) and primary zone holes (8.6%). In the intermediate zone the split was 3% cooling air, 10.5% from PZ holes and 3% from intermediate zone holes. The design data are summarized in Table 4-1. A schematic of A/Mod combustor assembly is seen in Figure 4.35, and an envelope of the basic can design is shown in Figure 4.36.

4.2.2 Atmospheric Rig Development - Class A/Mod Combustor

The atmospheric development of the Class A/Mod combustor was performed on the test facility at UACL. Early low pressure development was done using a pressure jet atomizer of Flow Number close to 1.0 . This resulted in providing a stable flame over the operating range with reasonably good combustion efficiency and lean limit blow out performance.

Emissions measurements were done at the two heavily weighted points on the simulated Federal Driving Cycle (Table 4-13) accounting for 56% of the cycle. To simulate the operating conditions on the simulated Federal Driving Cycle at atmospheric pressure, the ratio $\frac{W_{in}\sqrt{T_{in}}}{P_{in}}$ was kept constant over each of the operating conditions.

Based partly on Class UB combustor experience a choice was made fairly early in the development for an air-blast nozzle. This nozzle was identical to the one used with the Class UB combustor (Figure 4.3). As with UB, the use of the air-blast nozzle (Flow Number = 3.5) provided for more homogeneous mixing and leaner fuel-air mixture in the core of the primary zone. Stability problems at low fuel flows, encountered when using the air-blast nozzle, were overcome by incorporating a sleeve in the head end, which surrounded the fuel nozzle and served as a flame holder.

The main development theme was to keep the hardware simple and practical. The initial average fuel-air ratio in the primary zone corresponded to an equivalence ratio of 0.85. The methods attempted to reduce NO_x emissions were -

- Lean primary zone with rapid quench.
- Highly atomized, well mixed sprays with an air blast nozzle.
- Strongly penetrating (plunged) jets in primary zone.

Figure 4.37 shows the milestones in Class A/Mod combustor development employing the above approaches. The data refer to the maximum weighted condition on the simulated Federal Driving Cycle with an air inlet temperature of 980°F and far = 0.005. The Emission Index for this condition reduced from a value of 7.95 to 1.88 . Further leaning of the primary zone introduced stability problems during atmospheric test runs.

The air-blast nozzle provided a lean uniform flame, indicating good mixing.

Introduction of 'cool' regenerator bypass air into the primary zone was also attempted with encouraging results. This aspect of the investigation is referred to in detail in Section 4.2.5. Thirty-nine modifications in all were tested at atmospheric pressure before shipping the combustor to UARL for development under full pressure conditions.

4.2.3 Class A/Mod Pressure Development

During development, emissions were evaluated on an integrated basis over three points (FDC #2, 3 and 4) representing 78% of the simulated Federal Driving Cycle. Final evaluation on a chosen configuration was done over the entire cycle.

In all, twenty-six different configurations were evaluated for emissions (Appendix B-3). To start with, the combustor which had undergone preliminary development at UACL was evaluated and modifications involving reproportioning the air were attempted. Essentially leaner head end and early quench were attempted by moving the primary zone holes (A, Figure 4.40) and also increasing hole size (while maintaining pressure loss reasonably constant). No alterations being made in the head end, the emission indices for NO_x and CO fall in a band as shown in Figure 4.38.

As the flame stability appeared to be adversely affected with admission of more air through primary zone (A) holes, it was decided to increase swirl flow into the head end. This was done by modifying the head end assembly so as to introduce an additional swirler between the air-blast nozzle and the can swirler (Figure 4.40). This swirler provided for an area increase of about 30% for swirl-flow. The emissions for this system lie on the dotted line shown in Figure 4.38 (medium swirler), the two data points correspond to a proportional variation in air flow into primary zone accomplished by combustor modification in the dilution zone. The increased swirl flow rendered the flame more stable, enabling introduction of more air through the primary holes.

The medium swirler was replaced with a larger swirler so as to increase the area for swirl flow by another 25% approximately. This resulted in a further improvement in flame stability and the emission indices then fall on a curve closer to the target (high swirler - Figure 4.38) as the air into the primary zone was proportionally varied.

The UHC levels during all the development tests were well below target. It was apparent from the trends of the curves (Figure 4.38) that staged swirl in the primary zone and lean primary zone can yield good dividends in terms of simultaneous reductions in NO_x, as well as CO levels. However, the program status required a cut-off in further development and a choice had to be made on a configuration for final evaluation. Since the three other points on the simulated Federal Driving Cycle were expected to yield higher integrated levels of CO and lower integrated levels of NO_x, a configuration producing emissions shown by the shaded point was chosen for final evaluation.

The configuration and hole pattern of the combustor are shown in Figure 4.40 and flow splits in Table 4-14.

The results of final evaluation are discussed in a following section.

4.2.4 Effect of Atmospheric Moisture on Exhaust Emissions - Class A/Mod Combustor

Similar to the tests on Class UB combustor, investigations regarding the effect of inlet moisture on exhaust emissions of A/Mod combustor were undertaken. The results are shown in Figure 4.24 along with the observed effect on Class UB combustor. A direct comparison between the effects on the two combustors cannot be made due to the differing geometries and operating conditions. At standard humidity conditions the percentage reductions in NO_x over dry air operating conditions are 9.2% for FDC #2 and 12% for FDC #3. The reduced effect in the case of A/Mod is surprising but may be due to a richer primary zone (the geometry being considerably different to that used in final evaluation) or may be the effect of higher temperature of inlet air compared to the reaction zone temperature. Further analytical and experimental work would be required if any definite conclusions are to be drawn on the meaning of this effect.

4.2.5 Effect of Regenerative Bypass

The concept of regenerator bypass where a small fraction of compressor air is fed directly to the head end of the combuster was evaluated, at both atmospheric and full pressure conditions. During atmospheric development, cold bypass air was introduced through the swirler in the head end. The arrangement for the regenerator bypass test is shown in Figure 4.45 and the results shown in Figures 4.46 and 4.47. Figure 4.46 shows the variation of CO and NO_x emissions indices as the percentage of bypass air is increased. Also shown are the air temperatures as measured in the manifold. The data refer to atmospheric simulation of FDC #6. It is seen that CO emissions held steady, while NO_x decreased with increases in bypass flow. Figure 4.47 refers to data for FDC #2. Here the CO emissions increased with bypass air, while NO_x decreased. This may be the result of excessive quench in the core of the primary zone at the low primary zone fuel-air ratio corresponding to FDC #2.

Regenerator bypass under representative operating pressure conditions was evaluated briefly at the tail end of the development program at UARL. The results shown in Table 4-18 are disappointing in that increase in CO is more dominant than reduction in NO_x levels, as bypass air into the head end is increased. The combustor geometry corresponded to the configuration chosen for final evaluation (Figure 4.40). Bypass air was introduced into the head end at two locations, in one case through the can swirler (β) and in the other case through the air-blast nozzle. In both cases the bypass air appears to result in over-quenching of reactions inside the flame holder. It is believed, however, that this concept can be made to work if the combustor geometry is properly designed and bypass air admission is done in the proper area of the primary zone. For example, introducing the bypass air through the intermediate swirler or outside of the flame holder may be considered. The effect of bypass air on cycle efficiency and CO emission would determine the extent to which this approach may be utilized in reducting NO_x emissions.

4.2.6 Class A/Mod Combustor Final Evaluation

The combustor with the geometry shown in Figure 4.40 was chosen for final evaluation on the simulated Federal Driving Cycle (Table 4-13) and on the Steady Speed Mode (Table 4-16). The simulated Federal Driving Cycle data are presented as integrated emissions (Tabl [illegible] and Figure 4.41). The emission indices for Steady Speed Mode Ope [illegible] re presented as parametric curves (Figures 4.42, 4.43 and 4.44).

On the simulated Federal Driving Cycle, the integrated emissions are 86% below target on UHC, 45% above target on NO_x and 81% above target on CO (Table 4-13). The maximum temperatures obtainable with the facility was 1340 °F, thus the operating conditions on FDC #1 and FDC #5 are off-specification. These two conditions together represent only 21% of the FDC and hence the cycle emission values are reasonably representative.

Finally, the emissions levels from the Class A/Mod combustor were evaluated at the EPA specified test conditions listed in Table 4-16 which simulate operation at constant vehicle speeds. The results of emissions evaluation tests conducted at conditions corresponding to vehicle speeds between 50 and 108 miles per hour are summarized in Table 4-17. The variation of emission indices with vehicle speed is shown in Figure 4.42 and with fuel flow in Figures 4.43 and 4.44. The UHC emissions were very low over the entire operating range. Operation at higher power levels generally resulted in increasing the level of NO_x emissions and decreasing the level of CO emissions. However, since the transition from low-power to high-power is accomplished by simultaneously increasing the fuel-air ratio and decreasing the inlet temperature, more than one mechanism is responsible for changes in pollutant emissions.

TABLE 4-1 SUMMARY OF DESIGN DATA FOR EPA CLASS A/MOD & UB COMBUSTORS

Parameters	Class	
	A/Mod	UB
Inlet pressure (atm)	5	12
Air flow rate (lbs per sec)	1.50	1.1
Fuel flow rate (lbs per hour)	67	77
Fuel air ratio (overall)	0.0124	0.0195
Inlet air temp. (°R)	1560	1260
Outlet temp. (°R)	2360	2360
Pressure drop (%)	2.5	2.6
Reference velocity annulus (ft/sec)	106.4	76.3
Reference velocity - flametube (ft/sec)	74.2	78.1
Number of fuel nozzles	1	1
Fuel	JP4	JP4
Liner diameter (in.)	4	2.61
Liner length (in.)	9.5	5.56
Liner length - P Z (in)	2.0	1.33
Liner length - I Z (in)	2.88	2.67
Liner length - D Z (in)	4	1.56
Liner cross sectional area (in^2)	12.57	5.37
Liner volume - total (ft^3)	0.0691	0.0173
Liner volume - P Z (ft^3)	0.01454	0.00413
Heat release rate (MM BTU/hr. ft^3 atm) (based on total liner volume)	3.64	6.95
Heat release rate (MM BTU/HR. ft^3 atm) (based on P Z volume)	17.32	29.1
Casing Diameter (in.)	5.4	3.55

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TABLE 4-2 FEDERAL DRIVING CYCLE SIMULATED CONDITIONS FOR CLASS UB COMBUSTOR

FDC Point	P_{in}	T_{in}	W_{air}	far	TIME
	(psig)	(°F)	(lb/sec)		Percentage of Total Cycle
1	53	460	0.535	0.0052	3
2	46	425	0.500	0.0072	76
3	53	460	0.535	0.0104	20
4	46	425	0.500	0.0150	1

TABLE 4-3 CLASS UB COMBUSTOR EMISSIONS OVER SIMULATED FDC (ATMOSPHERIC TESTS WITH AIR-ASSIST NOZZLE)

SPECIES	INTEGRATED EMISSION INDEX (EI) 96% FDC	* TARGET
NO_x (AS NO_2)	1.15	1.19
UHC	5.25	1.22
CO	146.10	10.15

* Vehicle Economy = 8.6 MPG : Fuel = JP4

Zero Humidity

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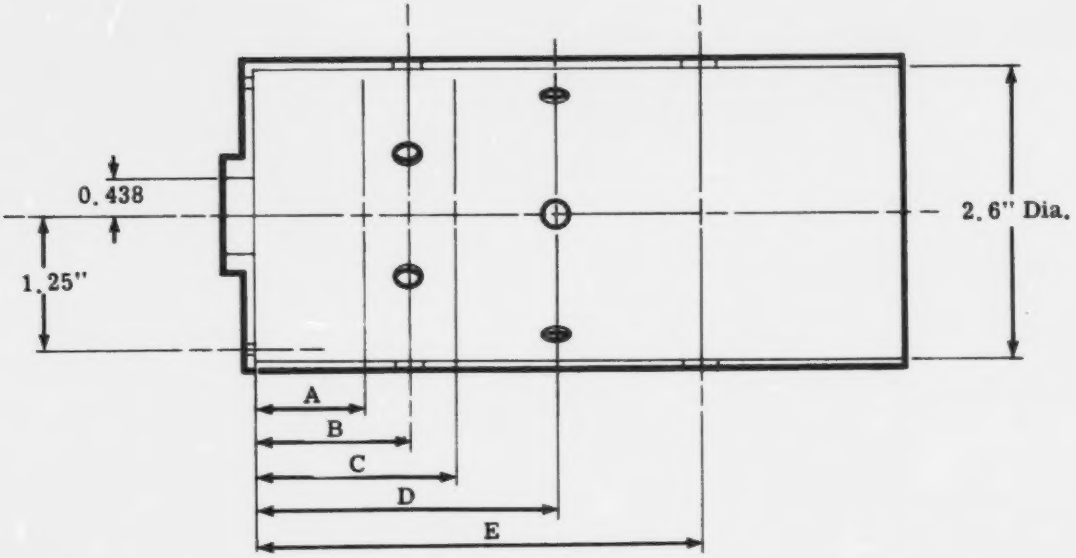
TABLE 4-4 CLASS UB COMBUSTOR GEOMETRY AND AIRFLOW DISTRIBUTION



Air Entry Designation	O	A	B	C	D	E	Comments
Axial Distance - Inches Percentage Airflow	0.0 17.5		1.33 46.3		2.66 50.0	4.00 100.0	Base Design
Axial Distance - Inches Percentage Airflow	0.0 20.3		0.75 62.8		1.33 66.5	2.66 100.0	Rapid Quench
Axial Distance - Inches Percentage Airflow	0.0 25.1		1.[illegible] 78.5		2.66 82.2	4.00 100.0	Lean Primary
Axial Distance - Inches Percentage Airflow	0.0 25.1		0.75 78.5		1.33 82.2	2.66 100.0	Lean Primary and Rapid Quench
Axial Distance - Inches Percentage Airflow	0.0 18.4	0.83 23.4	1.33 36.2	1.83 37.5	2.66 40.0	4.00 100.0	Atmospheric Pressure Tests at UACL

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TABLE 4-5 OPERATING CONDITIONS SELECTED FOR ANALYTICAL MODELING OF CLASS UB COMBUSTOR

Inlet Air Pressure	Inlet Air Temp.	Fuel-Air Ratio	Fuel Flow Rate	Air Flow Rate	Primary Zone Equivalence Ratio	Comments
(psia)	(F)		(lb_m/hr)	(lb_m/sec)		
175	800	0.0193	77.0	1.11	0.95	Base Design
175	800	0.0193	77.0	1.11	0.80	Rapid Quench
175	800	0.0193	77.0	1.11	0.70	Lean Primary
175	800	0.0193	77.0	1.11	0.70	Lean Primary and Rapid Quench
14.7	800	0.0209	7.32	0.0972	1.0	UACL Test Cond.
14.7	800	0.0188	6.58	0.0972	1.0	UACL Test Cond.
14.7	800	0.0167	5.83	0.0972	1.0	UACL Test Cond.
14.7	800	0.0147	5.15	0.0972	1.0	UACL Test Cond.

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TABLE 4-6 APPROXIMATE EQUIVALENT EXPRESSIONS FOR WATER VAPOR

Barometric Pressure 29.92 in. Hg.

Grains H_2O per lb. of Dry Air	Lbs. H_2O per lb. of Dry Air	Dew Point °F	Water Vapor Press. in. Hg.	Rel. Humidity % at 76°F	Remarks
20	0.0028	26	0.13	15	
40	0.0056	42	0.27	30	
60	0.0085	53	0.40	45	
75	0.0107	58	0.51	55	Standard
80	0.0112	61	0.53	59	
100	0.0143	67	0.66	74	
120	0.0171	72.2	0.80	89	

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TABLE 4-7 STEADY-SPEED MODE SIMULATED CONDITIONS FOR CLASS UB COMBUSTOR

VEHICLE SPEED	P_{in}	T_{in}	W_{air}	far	HP
(mph)	(psig)	(°F)	(lb/sec)		
30	46	425	0.50	0.0072	3
50	53	460	0.535	0.0104	15
60	60	490	0.575	0.0126	26
70	69	530	0.64	0.0139	41
80	83	585	0.71	0.0157	61
90	97	635	0.82	0.0166	82

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TABLE 4-8 EVALUATION OF FINAL CLASS UB COMBUSTOR IN SIMULATED STEADY-SPEED OPERATION

(ZERO HUMIDITY)

Vehicle Speed	Inlet Air Pressure	Inlet Air Temp.	Combustor Pressure Loss	Fuel-Air Ratio	Pollutant Emissions					
					NO_x (NO_2)		CO		UHC (C_6H_{14})	
(mph)	(psig)	(F)	$\frac{P_{in} - P_{out}}{P_{in}} \times 100$		EI	g/mi*	EI	g/mi*	EI	g/mi*
30	46	425	3.3	.00725	1.57	0.527	10.11	3.38	.210	.072
50	53	460	3.4	.01036	3.86	1.29	1.30	0.434	.057	.019
60	60	490	3.2	.01255	7.10	2.38	3.74	1.25	.105	.035
70	69	530	3.2	.0139	9.96	3.33	5.29	1.77	.009	.003
80	83	585	2.9	.0157	15.8	5.30	8.89	2.98	.010	.003
90	97	630	3.0	.0169	19.9	6.67	6.40	2.14	——	——

* Based upon assumed vehicle fuel economy of 8.6 miles/gal

Fuel: JP4

TABLE 4-9 RANGE MODE CONDITIONS FOR CLASS UB COMBUSTOR

LOW BASE LINE (50 mph)

P_{in} (psig)	T_{in} (°F)	W_a (lb/sec)	W_f (lb/hr)	far	HP
53	460	0.535	20	0.0104	15
37	460	0.409	15.3	0.0104	15
53	590	0.500	18.7	0.0104	15

TABLE 4-10 RANGE MODE CONDITIONS FOR CLASS UB COMBUSTOR

MEDIUM BASE LINE (70 mph)

P_{in} (psig)	T_{in} (°F)	W_a (lb/sec)	W_f (lb/hr)	far	HP
69	530	0.64	32	0.0139	41
69	420	0.678	33.8	0.0139	41
55	530	0.534	26.7	0.0139	41
80	530	0.725	36.2	0.0139	41
100	530	0.876	43.7	0.0139	41
129	530	1.098	55.0	0.0139	41

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TABLE 4-11 CLASS UB COMBUSTOR CONFIGURATION (FINAL) AND AIR FLOW DISTRIBUTION

HOLE	DIA. (INCHES)	NO. OFF	AIR FLOW	MIXTURE CONDITIONS		
				FDC #	FAR	ϕ_{PZ}
a''	.040	12	0.84	1	.0052	.315
B	.173	4	5.23			
A'	.089	24	7.96	2	.0072	.439
E'	.195	16	25.78			
E	.265	16	49.10	3	.0104	.631
NOZZLE ORIFICE			2.71			
NOZZLE SWIRLER			3.07	4	.0150	.911
HIGH PRIMARY SWIRLER			5.29			

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TABLE 4-12 CLASS UB COMBUSTOR EMISSIONS OVER SIMULATED FDC
(Full Pressure Tests with Air-Blast Nozzle)

(FINAL)

SPECIES	INTEGRATED EMISSIONS INDEX (EI)		*TARGET
	96% FDC	100% FDC	
UHC	0.177	1.464	1.220
CO	8.275	10.87	10.15
$NO_x(AS\ NO_2)^+$	1.541	1.538	1.19

* Vehicle economy 8.6 miles/gal., Fuel: JP4
+ Humidity corrected

TABLE 4-13 FEDERAL DRIVING CYCLE SIMULATED CONDITIONS FOR CLASS A/MOD COMBUSTOR

FDC POINT	P_{in} (psig)	T_{in} (°F)	W_a (lb/sec)	far	TIME Percentage of Total Cycle
1	18	1380	0.59	0.0028	3
2	13	980	0.44	0.0050	34
3	13	1000	0.44	0.0063	22
4	13	1100	0.44	0.0070	22
5	18	1380	0.59	0.0057	18
6	13	1000	0.44	0.0126	1

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TABLE 4-14 CLASS A/MOD COMBUSTOR CONFIGURATION (FINAL) AND AIR FLOW DISTRIBUTION

HOLE	DIA. (INCHES)	NO. OFF	AIR FLOW %	MIXTURE CONDITIONS		
				FDC #	far	ϕ_{PZ}
β	0.166	10	7.50	1	0.0028	0.135
ν	0.125	8	-	2	0.0051	0.241
α	0.120	36	14.11	3	0.0063	0.301
A	0.113	32	11.16	4	0.0069	0.331
E'	0.226	12	16.66	5	0.0056	0.270
E	0.348	12	39.52	6	0.0126	0.602
NOZZLE ORIFICE			1.68			
NOZZLE SWIRLER			1.91			
HIGH PRIMARY SWIRLER			7.48			

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TABLE 4-15 CLASS A/MOD COMBUSTOR EMISSIONS OVER SIMULATED FDC
(Full Pressure Tests with Air-Blast Nozzle)

(FINAL)

SPECIES	INTEGRATED EMISSIONS INDEX (EI) 100% FDC	TARGET*
UHC	0.242	1.81
CO	27.09	14.90
NO_x (AS NO_2) (Humidity corrected)	2.54	1.75

* Vehicle Economy 12.7 miles/gal. Fuel = JP4

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TABLE 4-16 STEADY-SPEED MODE SIMULATED CONDITIONS FOR CLASS A/MOD COMBUSTOR

VEHICLE SPEED (mph)	P_{in} (psig)	T_{in} (F)	W_{air} (lb/sec)	far
50	18	1380	0.59	0.0057
70	25	1120	0.74	0.0075
90	40	960	1.06	0.0105
108	59	1100	1.50	0.0124

TABLE 4-17 EVALUATION OF FINAL CLASS A/MOD COMBUSTOR IN SIMULATED STEADY-SPEED OPERATION

(ZERO HUMIDITY)

Vehicle Speed	Inlet Air Pressure	Inlet Air Temp.	Combustor Pressure Loss	Fuel-Air Ratio	Pollutant Emissions					
					NO_x (NO_2)		CO		UHC (C_6H_{14})	
(mph)	(psig)	(°F)	$\frac{P_{in} - P_{out}}{P_{in}} \times 100$		EI	g/mi*	EI	g/mi*	EI	g/mi*
50	18	1330	11.9	0.0056	4.62	1.05	4.97	1.13	0†	0†
70	25	1120	11.7	0.0075	4.67	1.06	1.48	0.335	0.02	0.004
90	40	960	—	0.0105	5.55	1.26	0.595	0.135	0†	0†
108	59	1100	—	0.0124	9.17	2.08	0.387	0.088	0†	0†

* Based upon assumed vehicle fuel economy of 12.7 miles/gal

† Less than 0.1 ppm C

Fuel: JP4

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TABLE 4-18 EFFECT OF REGENERATOR BYPASS ON EMISSIONS

T_{in} = 1000°F, far = 0.0063

% BYPASS AIR (BY WEIGHT)	TEMP. OF BYPASS AIR °F	CO PPM	UHC PPMC	NO_x † PPM	REMARKS
0	—	96	—	9.9	NO BYPASS
5	553	30	3.1		Can Swirler Bypass
7.5	403	50	-	11.24	
10	315	130	-	11.08	
12.5	248	340	-	10.30	
15	210	490	7.1	8.56	
2	450	390	8.2	5.58	Injector Bypass
2.75	341	>500	44.4	2.26	
3.25	295	>500	113.2	1.3	
5.0	230	>500	169.0	0.9	

† Dry air - not corrected for humidity

Fuel: JP4

FIGURE 4.1 CLASS UB WATER ANALOGY MODEL

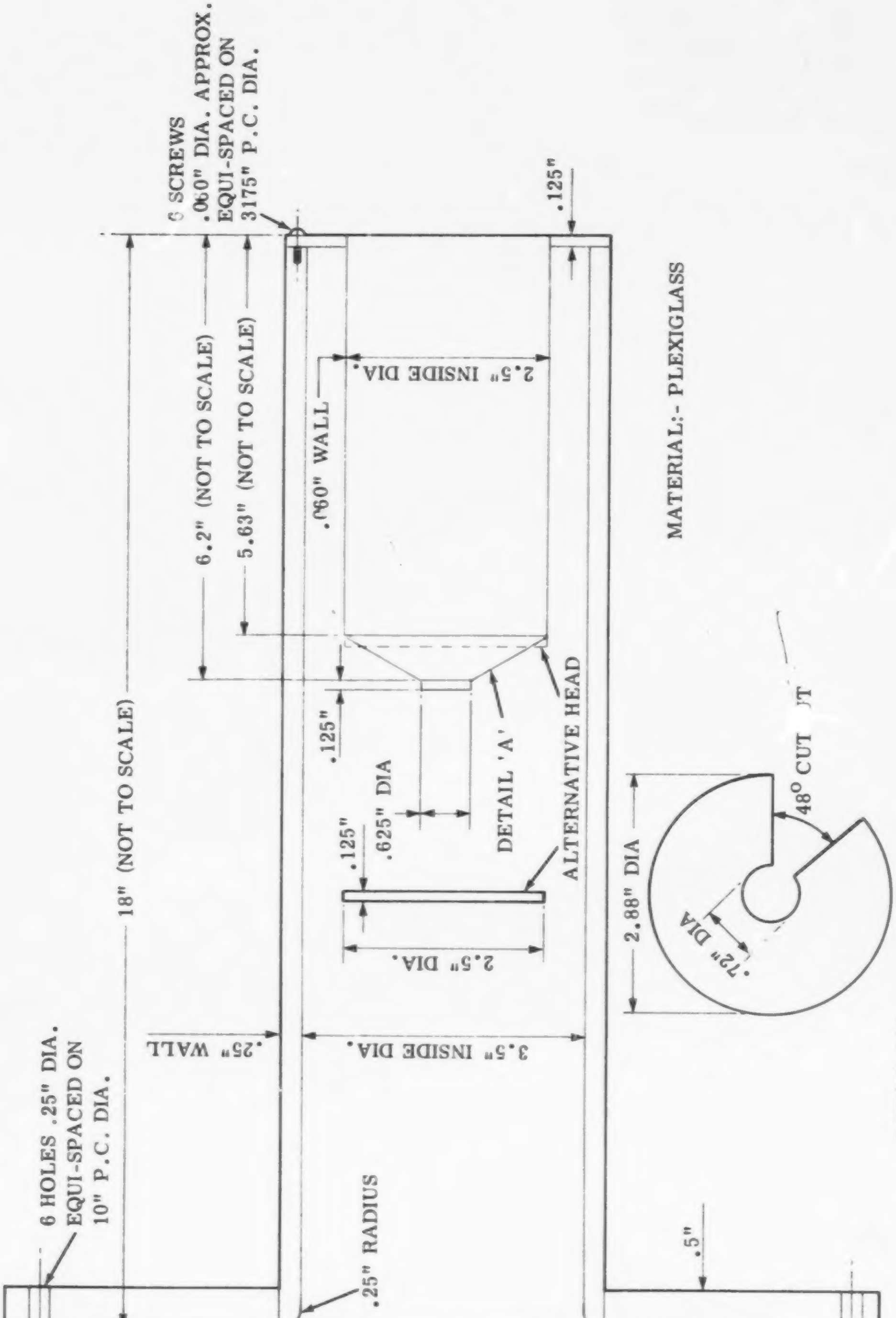
6 SCREWS
.060" DIA. APPROX.
EQUI-SPACED ON
3175" P.C. DIA.
.125"
6.2" (NOT TO SCALE)
5.63" (NOT TO SCALE)
2.5" INSIDE DIA.
.060" WALL
MATERIAL:- PLEXIGLASS
.125"
.625" DIA
DETAIL 'A'
ALTERNATIVE HEAD
.125"
2.5" DIA.
18" (NOT TO SCALE)
48° CUT OUT
2.88" DIA
.72" DIA
.25" WALL
3.5" INSIDE DIA.
6 HOLES .25" DIA.
EQUI-SPACED ON
10" P.C. DIA.
.25" RADIUS
.5"
11" DIA
DETAIL 'A'
MATERIAL THICKNESS:- .030"

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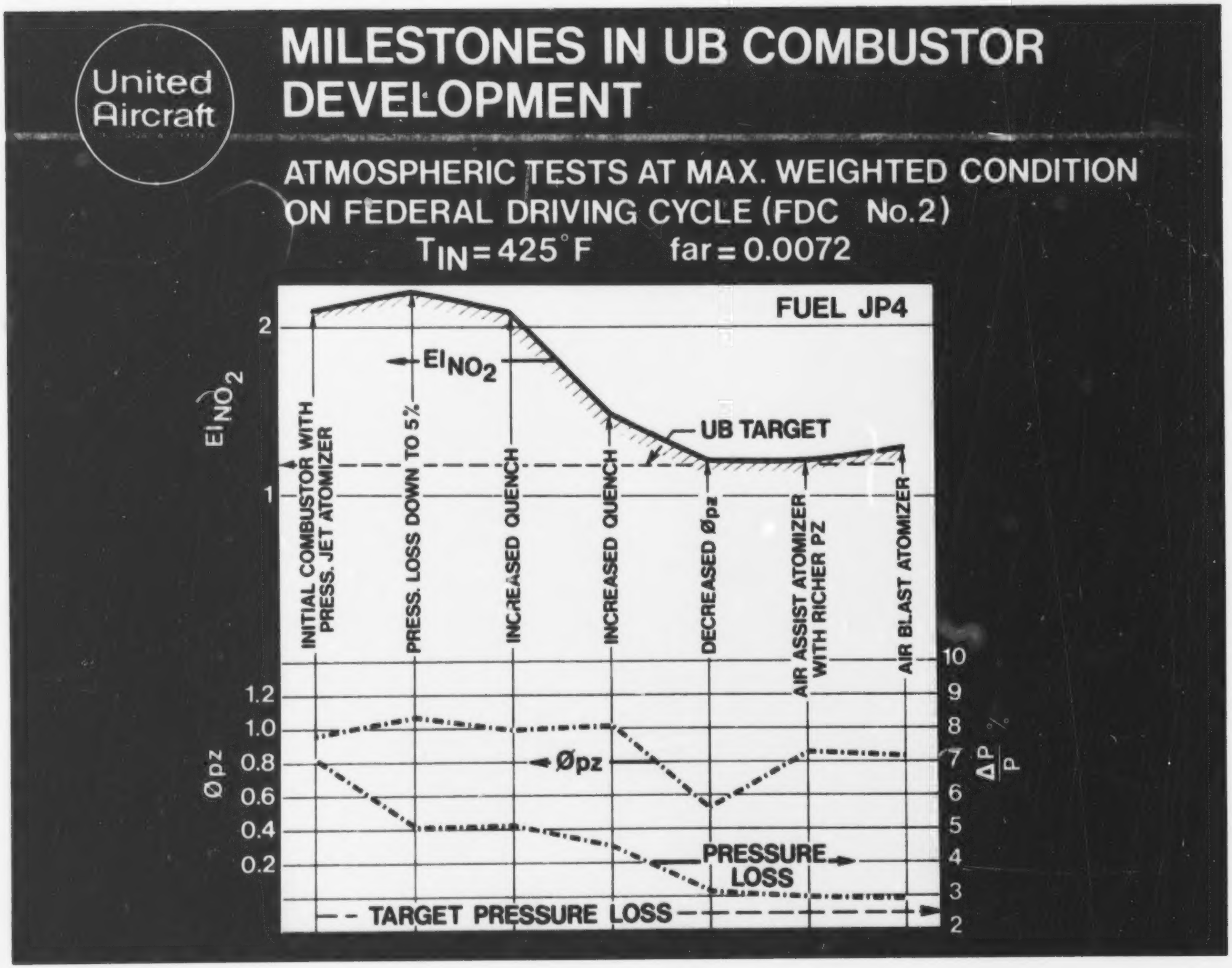
FIGURE 4.2 MILESTONES IN CLASS UB COMBUSTOR DEVELOPMENT
(ATMOSPHERIC TESTS AT UACL)



United Aircraft

MILESTONES IN UB COMBUSTOR DEVELOPMENT

ATMOSPHERIC TESTS AT MAX. WEIGHTED CONDITION ON FEDERAL DRIVING CYCLE (FDC No.2)

$T_{IN} = 425°F$ far = 0.0072

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FIGURE 4.3 CROSS SECTIONS OF FUEL NOZZLES

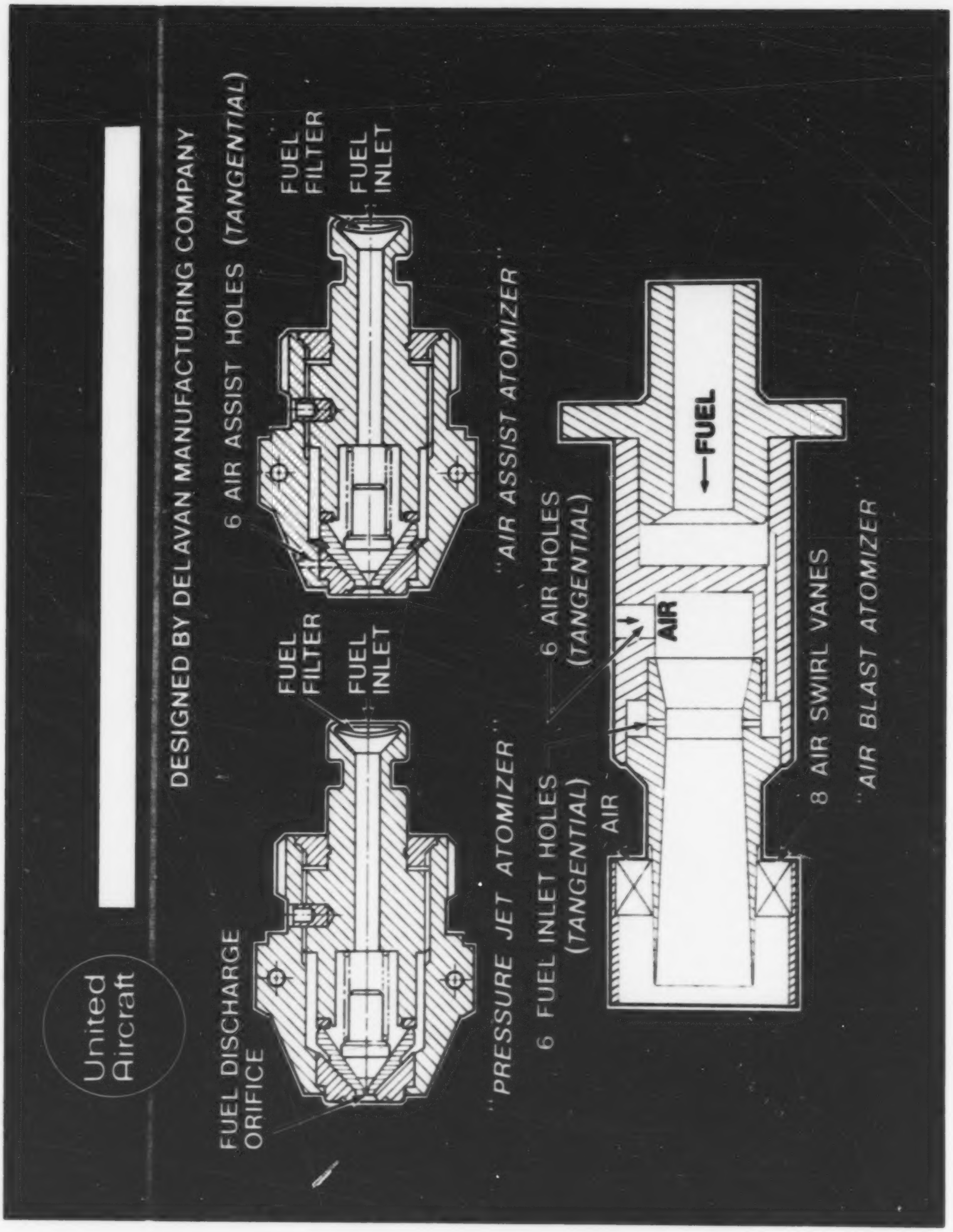
United Aircraft
DESIGNED BY DELAVAN MANUFACTURING COMPANY
FUEL DISCHARGE ORIFICE
FUEL FILTER
FUEL INLET
"PRESSURE JET ATOMIZER"
6 AIR ASSIST HOLES (TANGENTIAL)
FUEL FILTER
FUEL INLET
"AIR ASSIST ATOMIZER"
6 FUEL INLET HOLES (TANGENTIAL)
AIR
6 AIR HOLES (TANGENTIAL)
AIR
FUEL
8 AIR SWIRL VANES
"AIR BLAST ATOMIZER"

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FIGURE 4.4 FUEL ATOMIZERS USED IN CLASS UB COMBUSTOR DEVELOPMENT

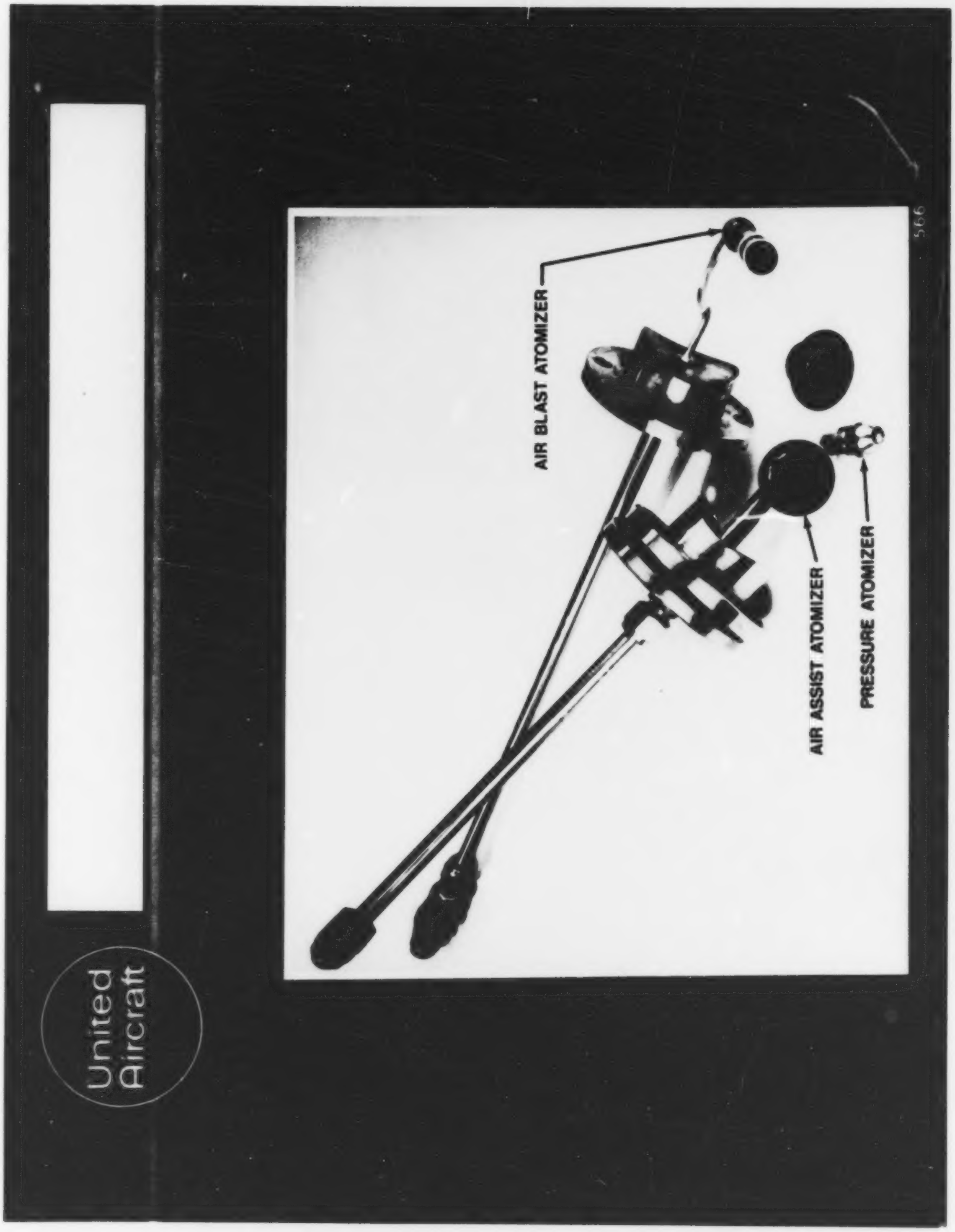
AIR BLAST ATOMIZER
AIR ASSIST ATOMIZER
PRESSURE ATOMIZER
566
United Aircraft

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FIGURE 4.5 SUMMARY OF ATMOSPHERIC TESTS ON CLASS UB COMBUSTOR

United Aircraft

ATMOSPHERIC TESTS -
UB COMBUSTOR - SUMMARY

$T_{IN} = 425\,°F$ PRESSURE ATOMIZER

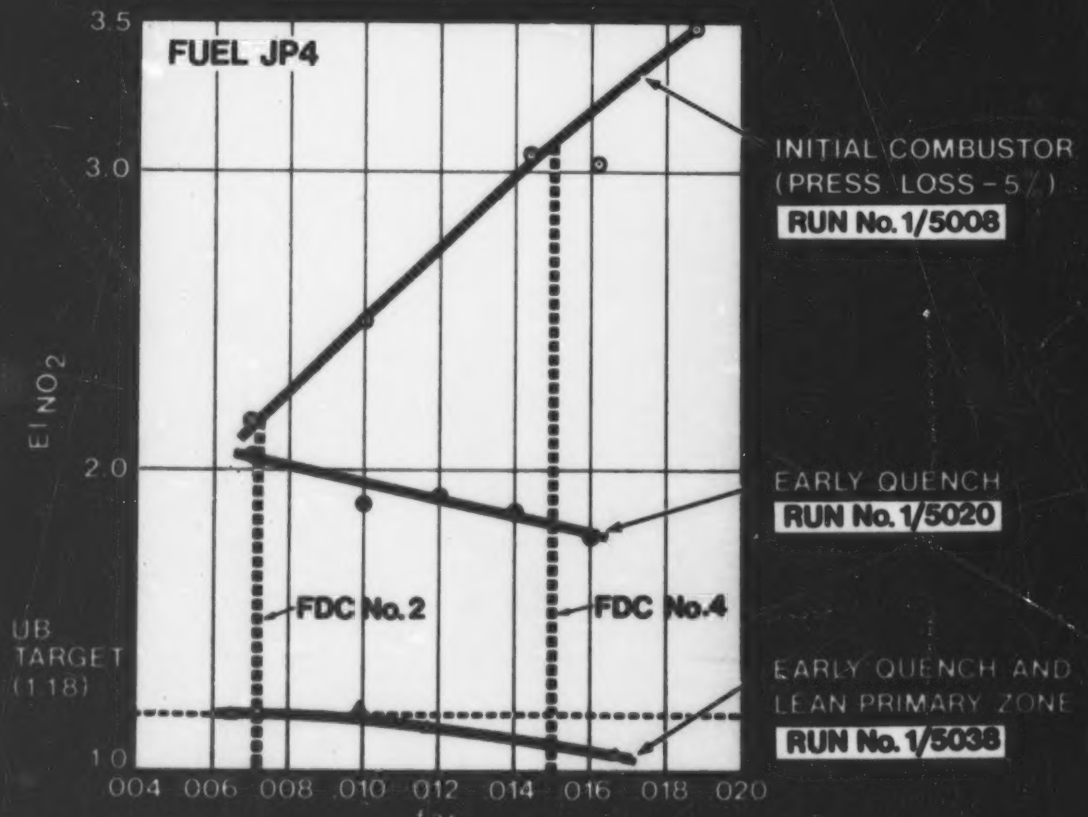

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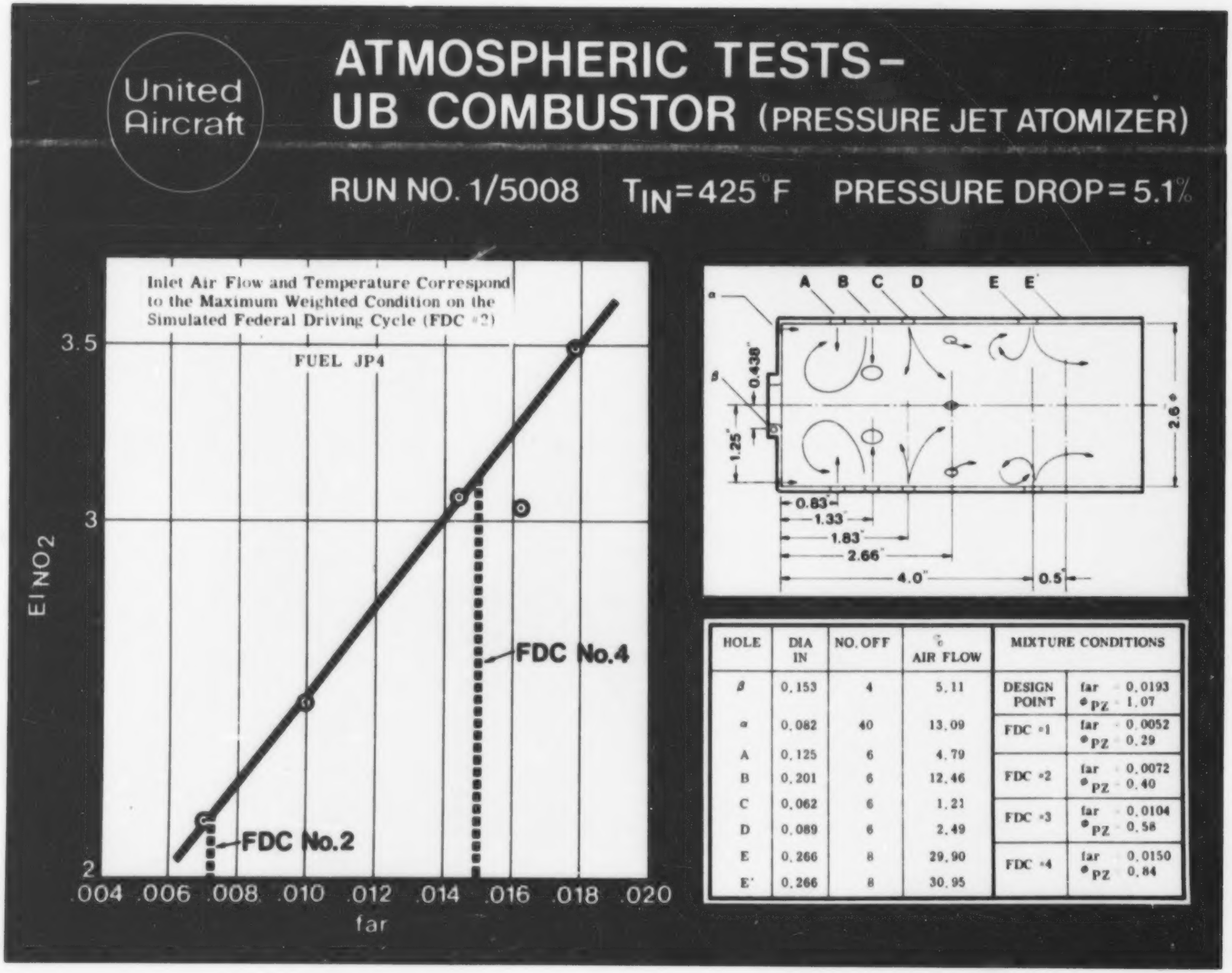
FIGURE 4.6 ATMOSPHERIC TESTS ON CLASS UB COMBUSTOR - INITIAL COMBUSTOR



United Aircraft

ATMOSPHERIC TESTS - UB COMBUSTOR (PRESSURE JET ATOMIZER)

RUN NO. 1/5008 $T_{IN} = 425°F$ PRESSURE DROP = 5.1%

Inlet Air Flow and Temperature Correspond to the Maximum Weighted Condition on the Simulated Federal Driving Cycle (FDC #2)

FUEL JP4

HOLE	DIA IN	NO. OFF	% AIR FLOW
β	0,153	4	5,11
α	0,082	40	13,09
A	0,125	6	4,79
B	0,201	6	12,46
C	0,062	6	1,21
D	0,089	6	2,49
E	0,266	8	29,90
E'	0,266	8	30,95

MIXTURE CONDITIONS	
DESIGN POINT	far = 0,0193 ϕ_{PZ} = 1,07
FDC #1	far = 0,0052 ϕ_{PZ} = 0,29
FDC #2	far = 0,0072 ϕ_{PZ} = 0,40
FDC #3	far = 0,0104 ϕ_{PZ} = 0,58
FDC #4	far = 0,0150 ϕ_{PZ} = 0,84

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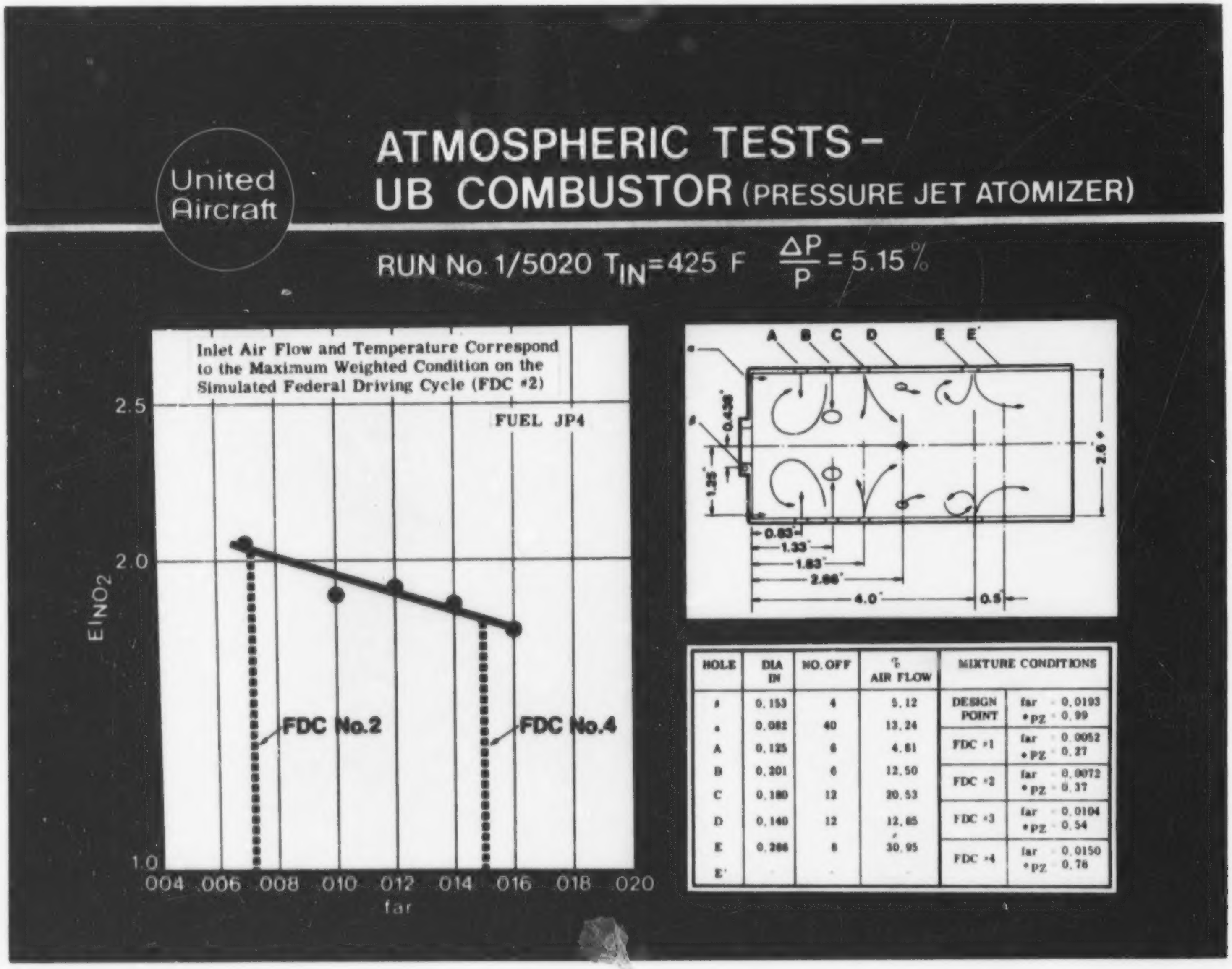
FIGURE 4.7 ATMOSPHERIC TESTS ON CLASS UB COMBUSTOR - EARLY QUENCH COMBUSTOR



United Aircraft

ATMOSPHERIC TESTS - UB COMBUSTOR (PRESSURE JET ATOMIZER)

RUN No. 1/5020 T_{IN}=425 F $\frac{\Delta P}{P}$ = 5.15 %

Inlet Air Flow and Temperature Correspond to the Maximum Weighted Condition on the Simulated Federal Driving Cycle (FDC #2)

FUEL JP4

HOLE	DIA IN	NO. OFF	% AIR FLOW	MIXTURE CONDITIONS	
ø	0.153	4	5.12	DESIGN POINT	far = 0.0193 •PZ = 0.99
•	0.082	40	13.24		
A	0.125	6	4.81	FDC #1	far = 0.0052 •PZ = 0.27
B	0.201	6	12.50	FDC #2	far = 0.0072 •PZ = 0.37
C	0.180	12	20.53		
D	0.140	12	12.85	FDC #3	far = 0.0104 •PZ = 0.54
E	0.266	8	30.95	FDC #4	far = 0.0150 •PZ = 0.76
E'	-	-	-		

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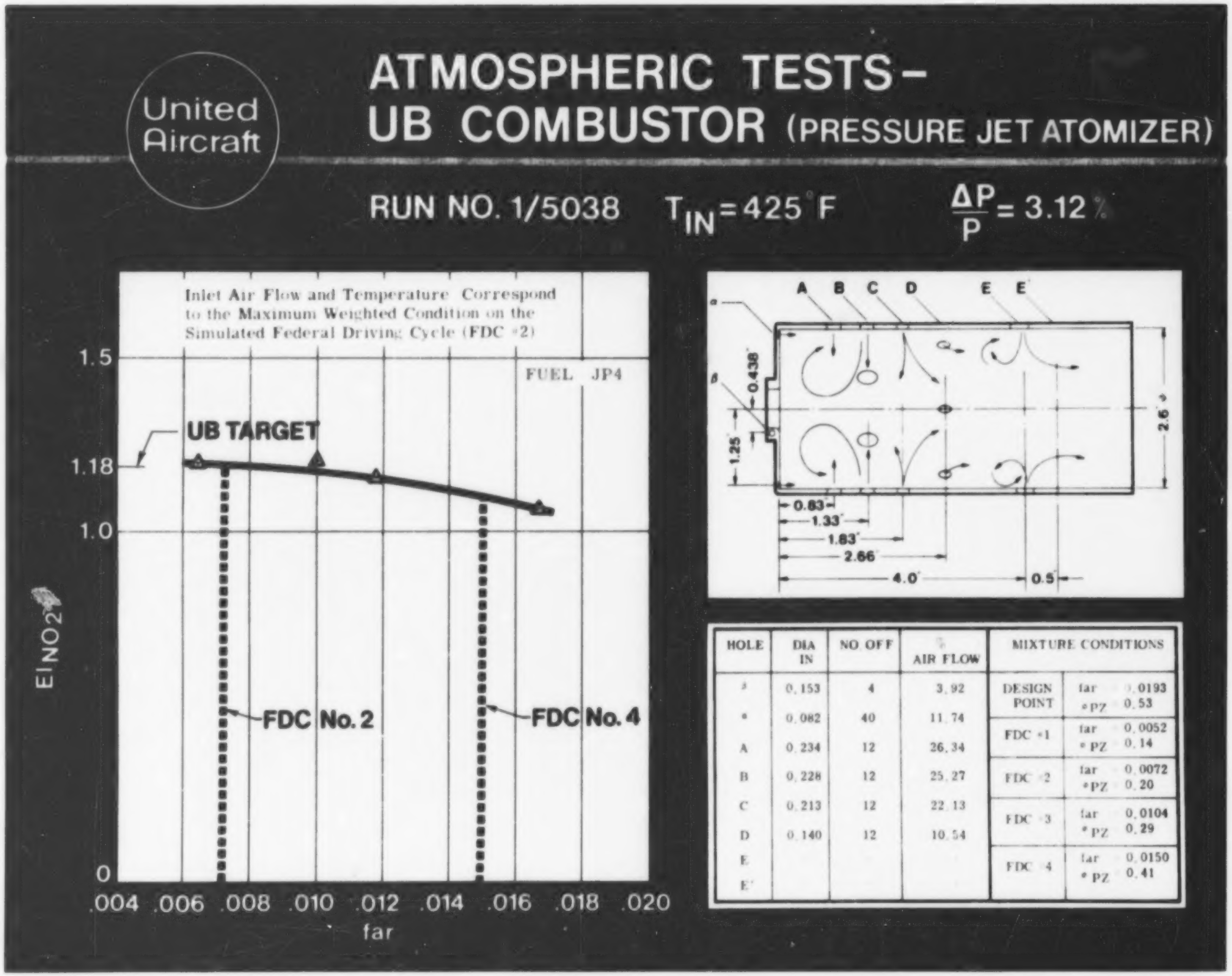
FIGURE 4.8 ATMOSPHERIC TESTS ON CLASS UB COMBUSTOR - EARLY QUENCH AND LEAN PRIMARY ZONE COMBUSTOR



United Aircraft

ATMOSPHERIC TESTS - UB COMBUSTOR (PRESSURE JET ATOMIZER)

RUN NO. 1/5038 $T_{IN} = 425°F$ $\frac{\Delta P}{P} = 3.12\%$

Inlet Air Flow and Temperature Correspond to the Maximum Weighted Condition on the Simulated Federal Driving Cycle (FDC #2)

HOLE	DIA IN	NO OFF	% AIR FLOW
β	0.153	4	3.92
α	0.082	40	11.74
A	0.234	12	26.34
B	0.228	12	25.27
C	0.213	12	22.13
D	0.140	12	10.54
E			
E'			

MIXTURE CONDITIONS	
DESIGN POINT	far = 0.0193 φ PZ = 0.53
FDC #1	far = 0.0052 φ PZ = 0.14
FDC #2	far = 0.0072 φ PZ = 0.20
FDC #3	far = 0.0104 φ PZ = 0.29
FDC #4	far = 0.0150 φ PZ = 0.41

FUEL JP4
UB TARGET
FDC No. 2
FDC No. 4
EINO2
1.5
1.18
1.0
0
.004
.006
.008
.010
.012
.014
.016
.018
.020
far
A
B
C
D
E
E'
α
β
0.438
1.25
2.6
0.83
1.33
1.83
2.66
4.0
0.5

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FIGURE 4.9 CLASS UB COMBUSTOR AFTER DEVELOPMENT AT ATMOSPHERIC PRESSURE (AT UACL)

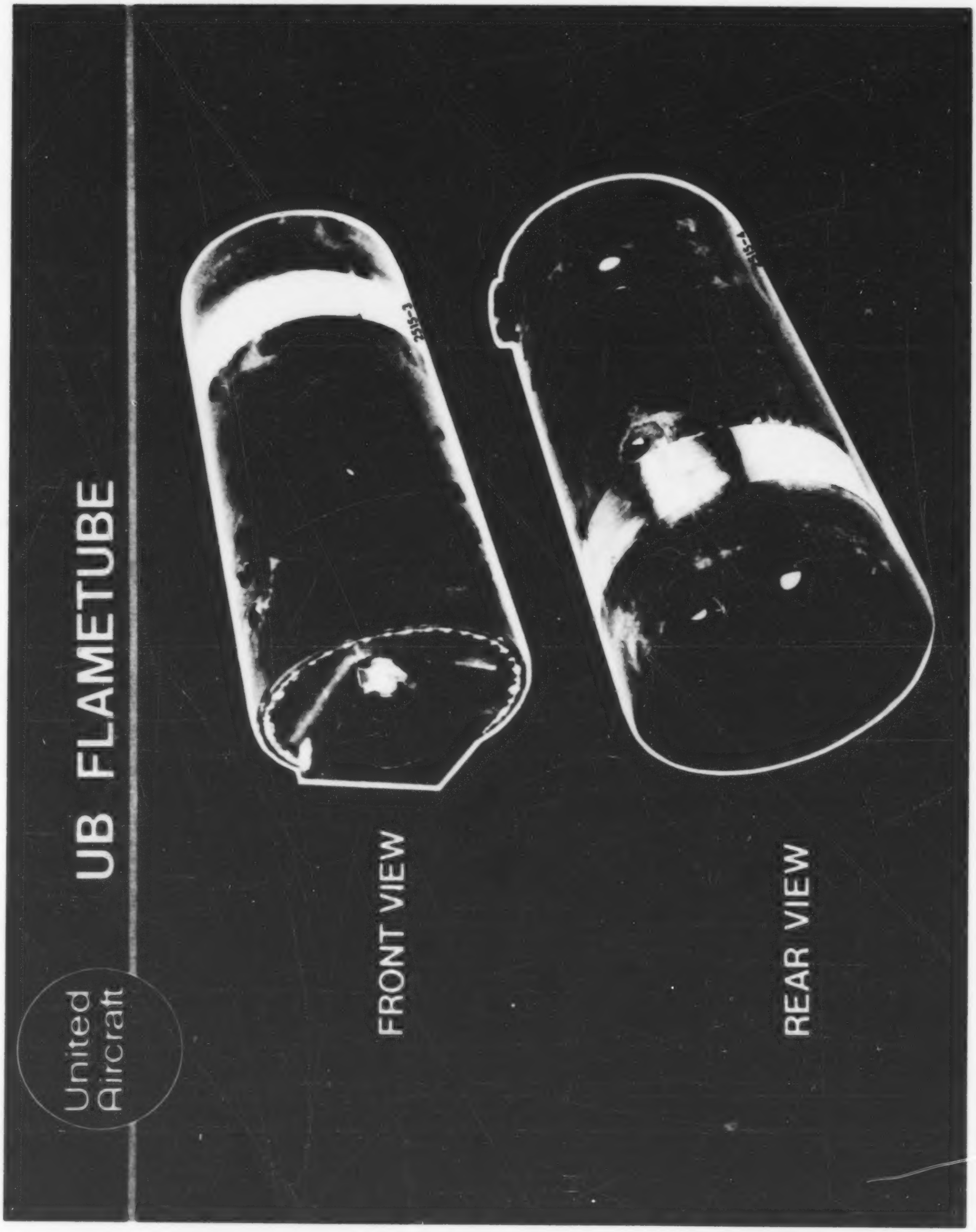
UB FLAMETUBE
United Aircraft
FRONT VIEW
REAR VIEW
2115-3
2115-4

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FIGURE 4.10 CLASS UB COMBUSTOR CASING

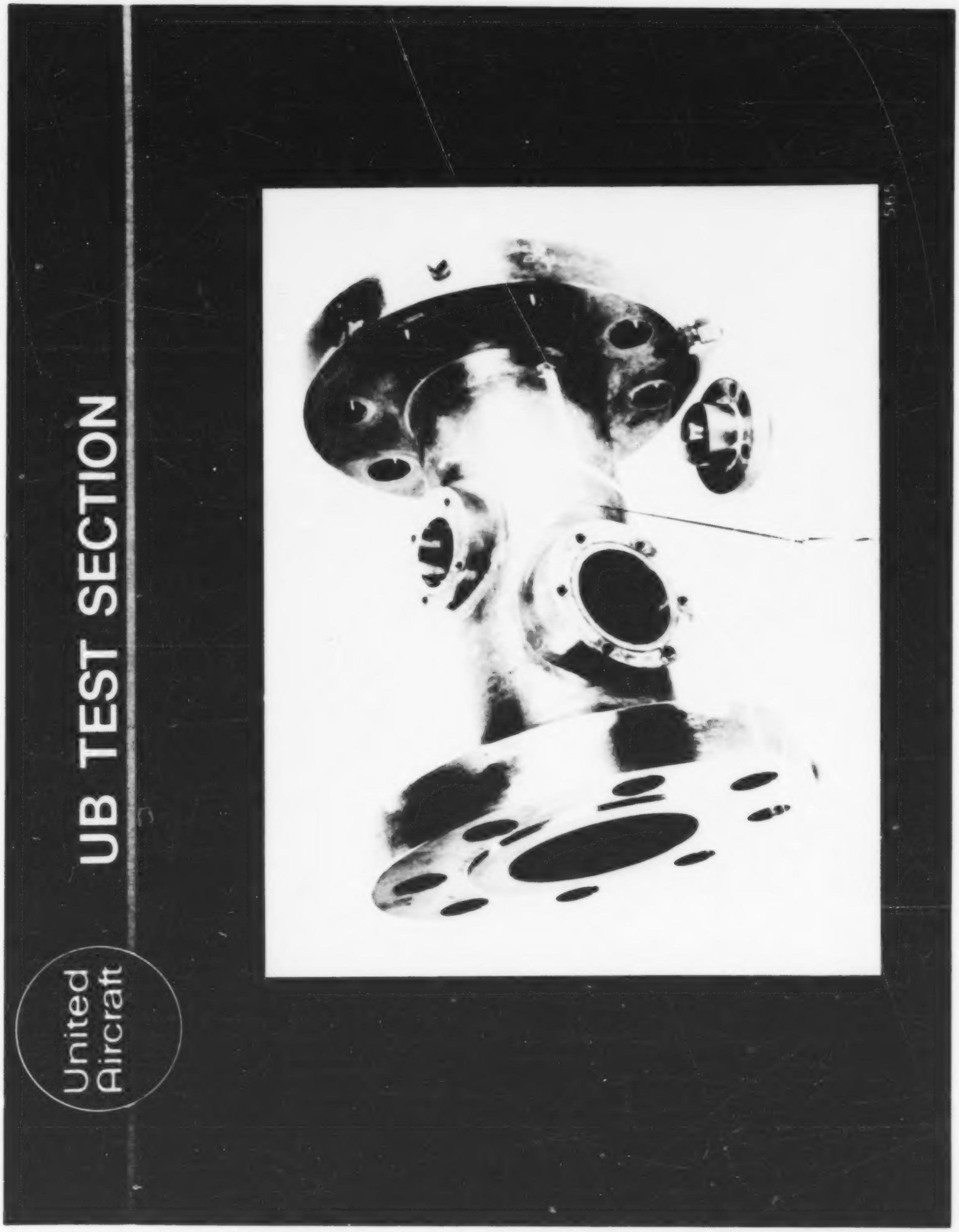
UB TEST SECTION
United Aircraft

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FIGURE 4.11 EFFECT OF PRIMARY ZONE EQUIVALENCE RATIO AND QUENCHING RATE ON NO_X EMISSIONS FROM CLASS UB COMBUSTOR

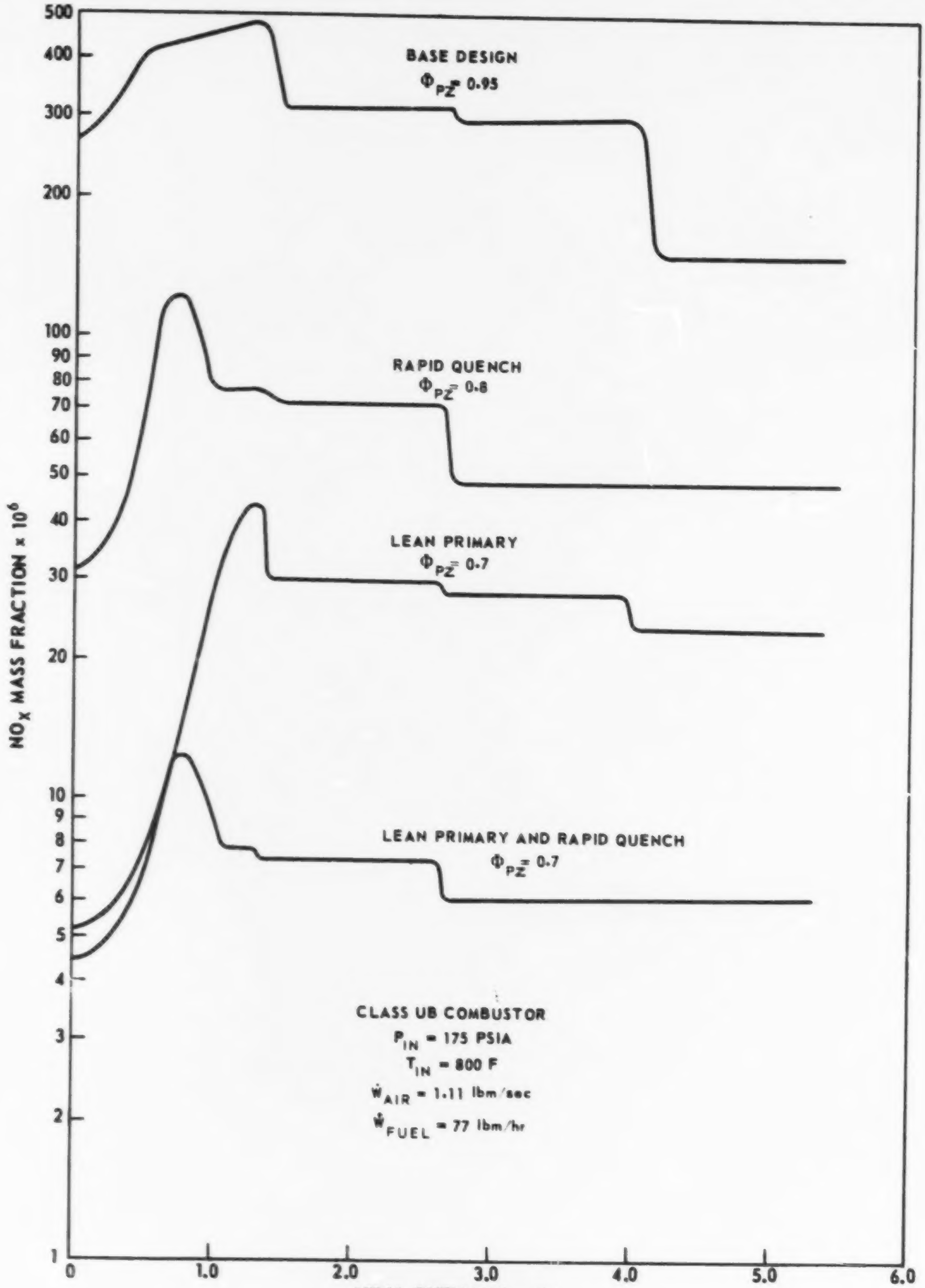

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FIGURE 4.12 COMPARISON OF MEASURED AND PREDICTED NO_X EMISSIONS FOR CLASS UB COMBUSTOR AT ATMOSPHERIC PRESSURE

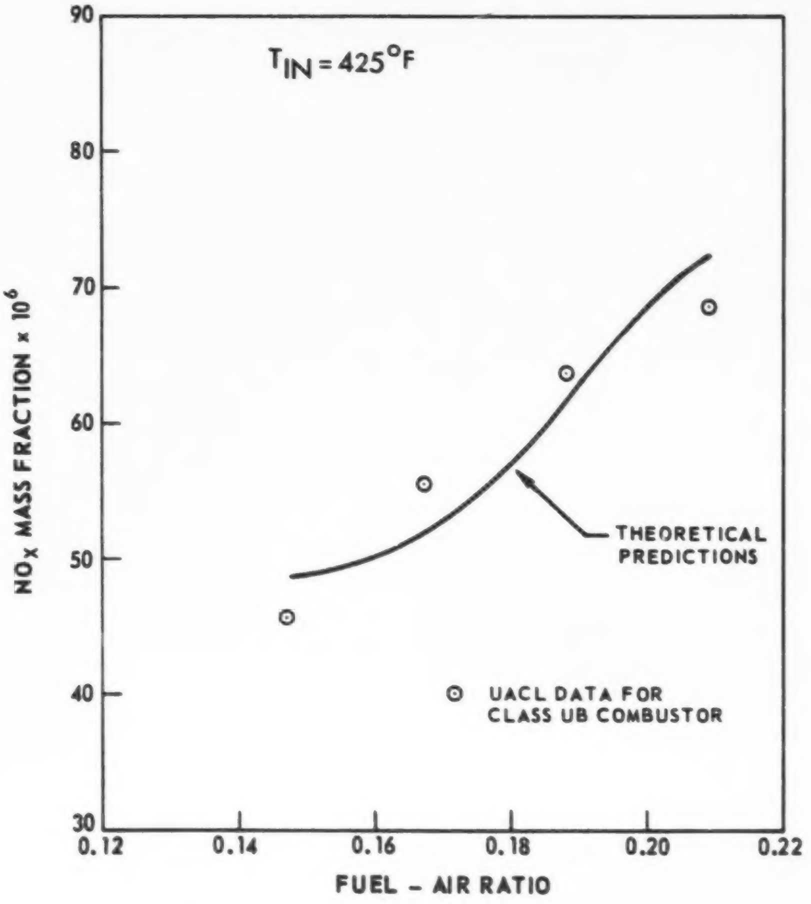

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FIGURE 4.13 EFFECT OF PRIMARY ZONE EQUIVALENCE RATIO AND RESIDENCE TIME ON NITRIC OXIDE EMISSIONS

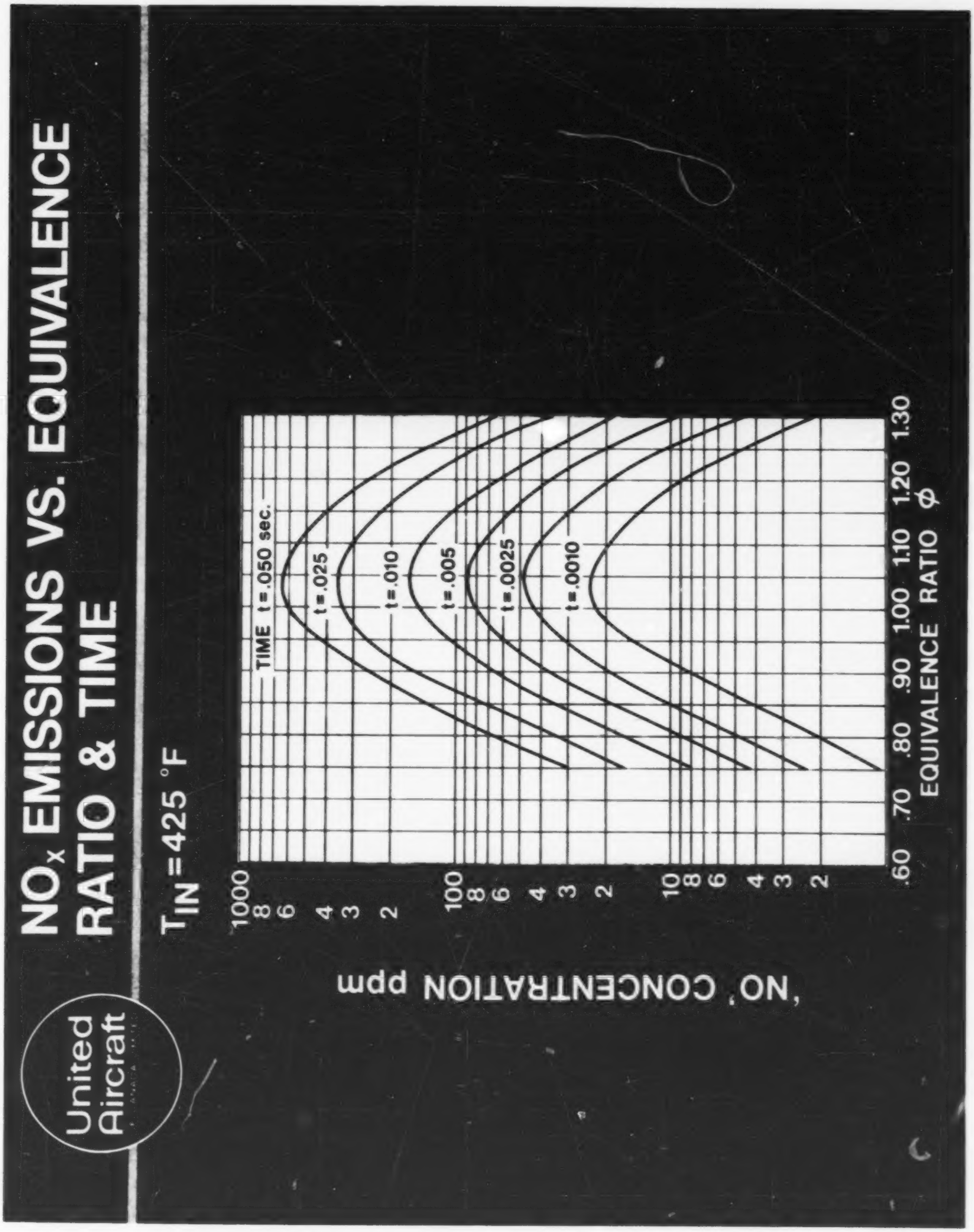

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FIGURE 4.14 EFFECT OF INLET PRESSURE ON NO_X EMISSIONS FROM CLASS UB COMBUSTOR

$T_{INLET} = 425$ F

$far_{OVERALL} = 0.0072$

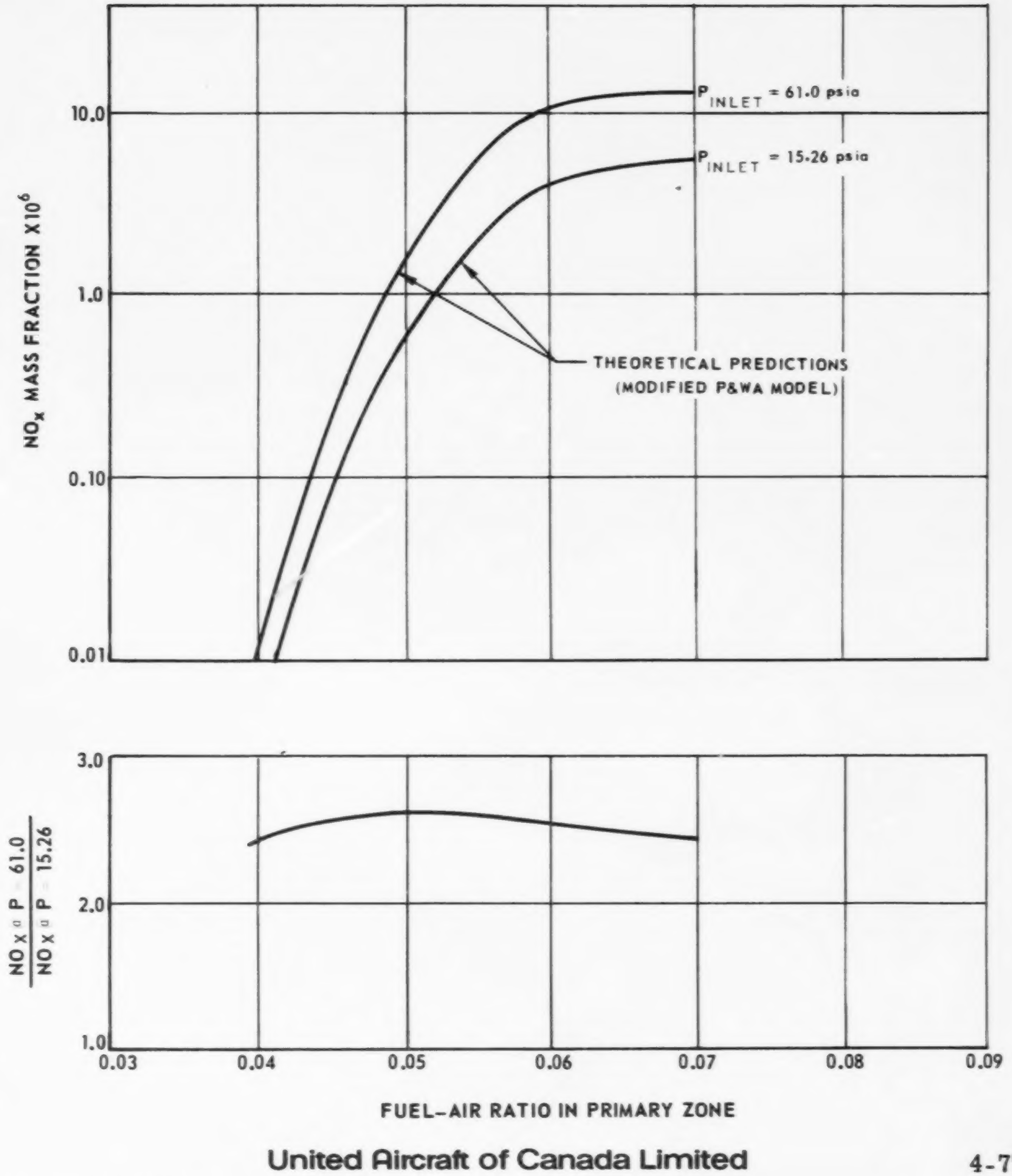

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FIGURE 4.15 EFFECT OF HUMIDITY ON NO_X EMISSIONS FROM CLASS UB COMBUSTOR

$T_{INLET} = 425$ F
$P_{INLET} = 61.0$ psia
$far_{OVERALL} = 0.0072$

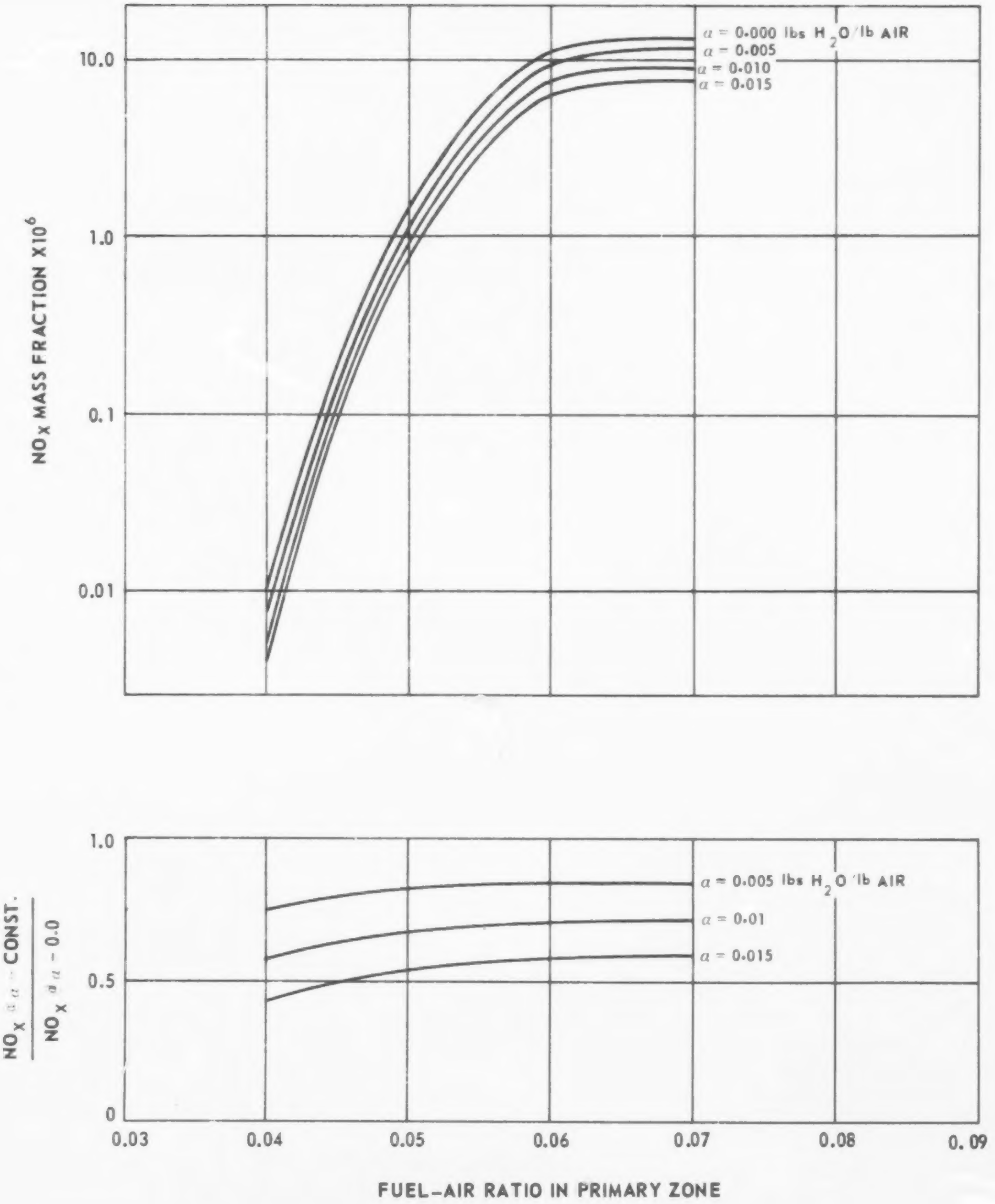

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FIGURE 4.16 VARIATION OF EQUILIBRIUM COMBUSTION TEMPERATURE WITH FUEL-AIR RATIO

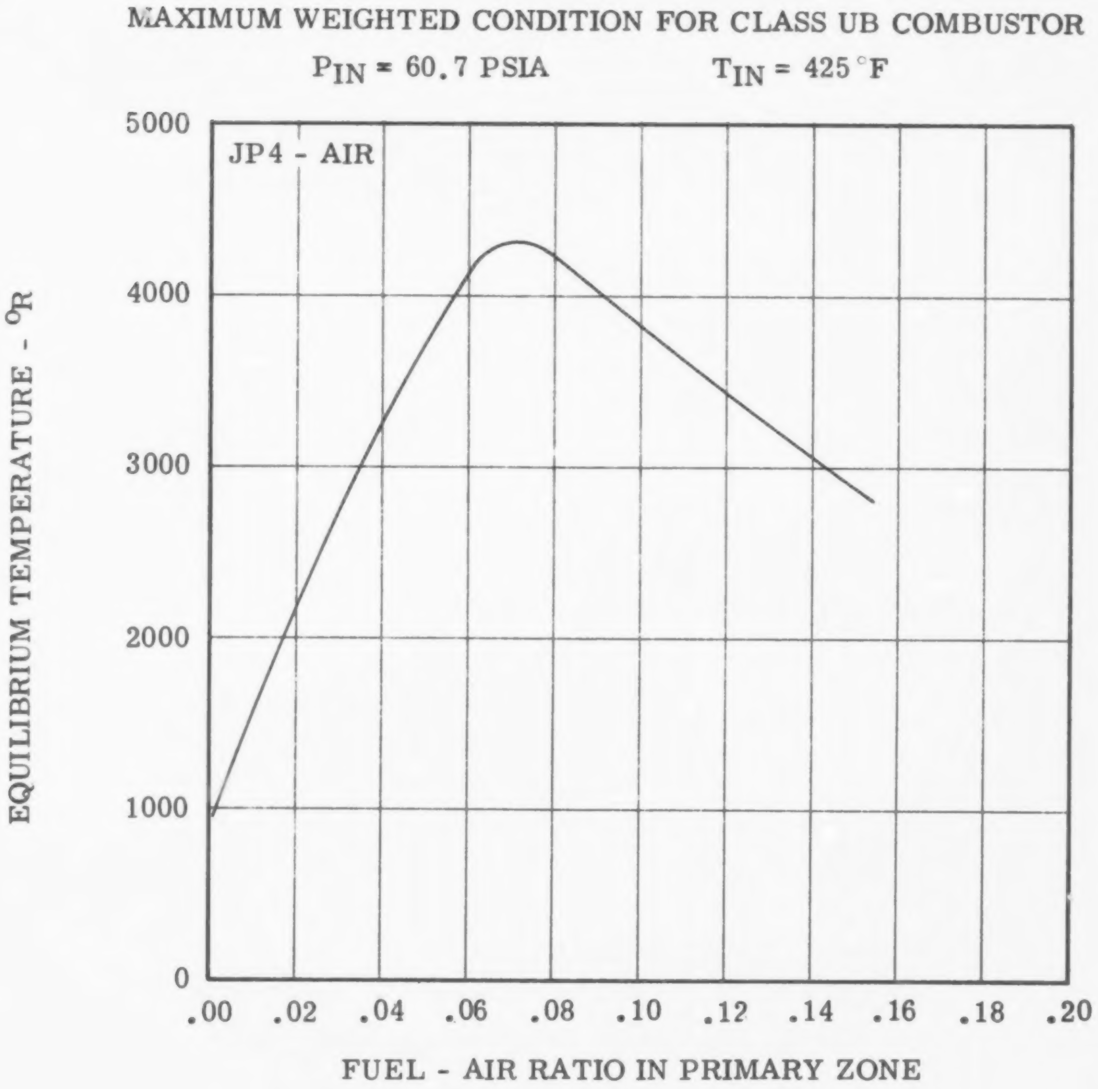

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FIGURE 4.17 VARIATION OF EQUILIBRIUM CO MOLE FRACTION WITH FUEL-AIR RATIO

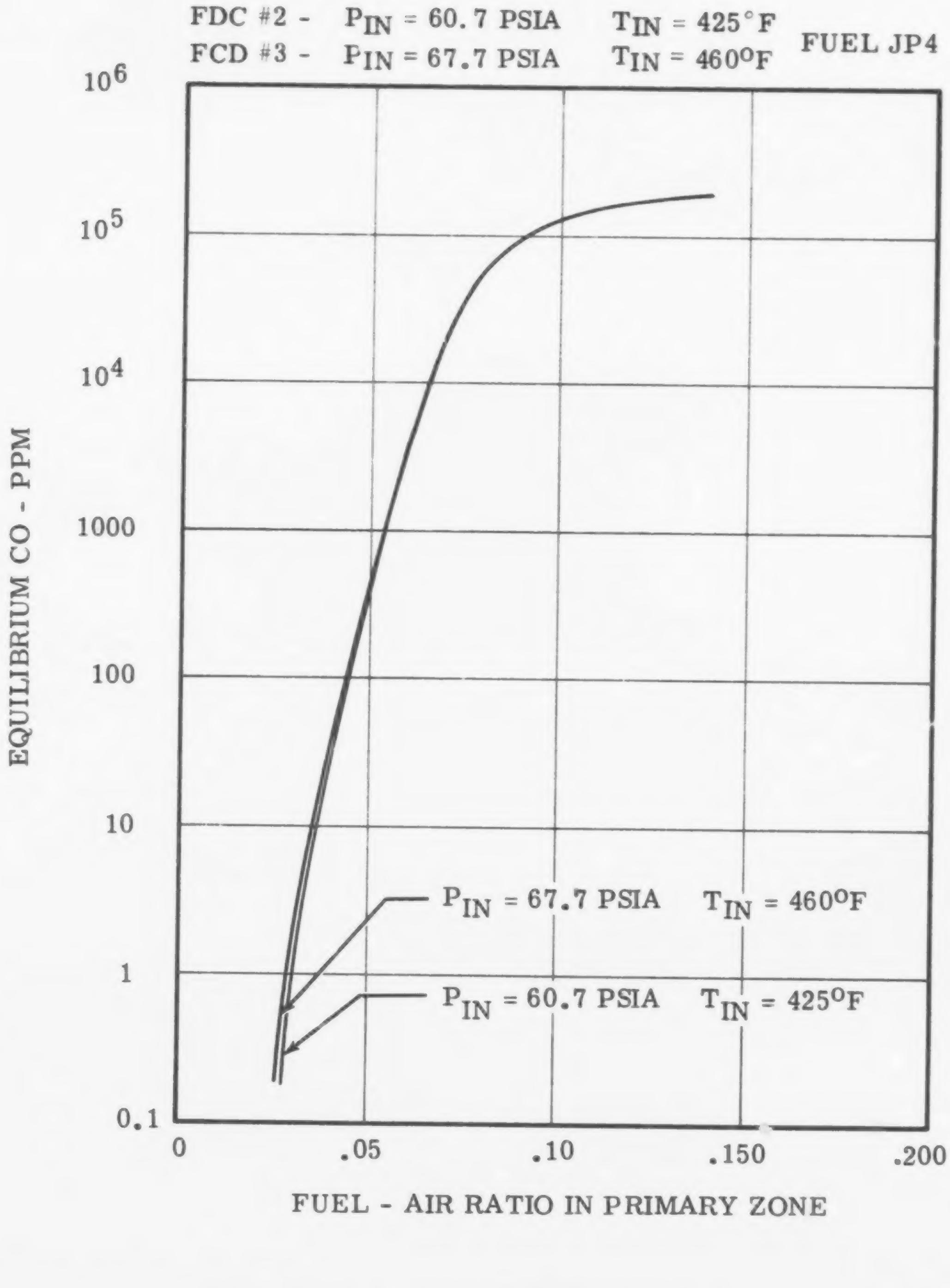

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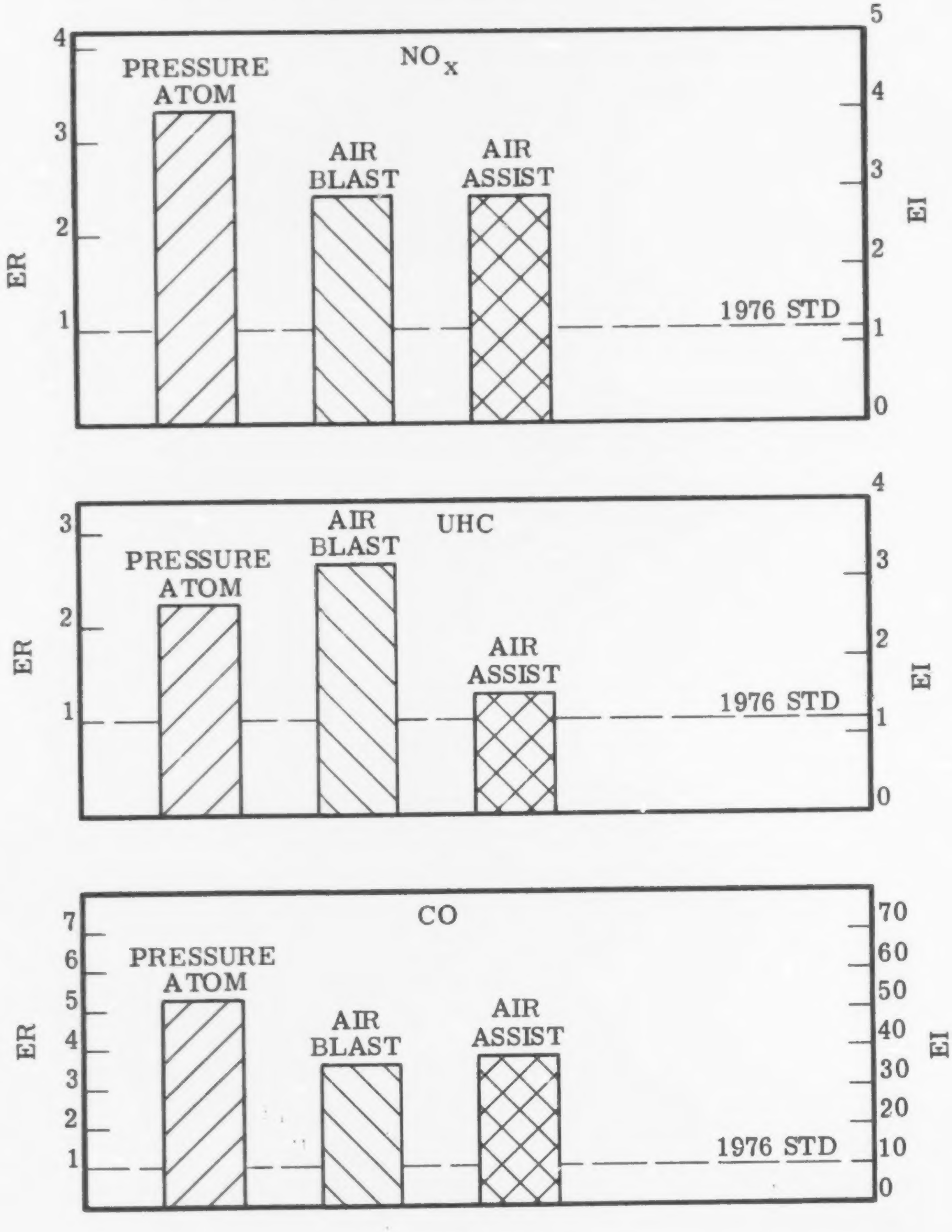
FIGURE 4. 18 SUMMARY OF EMISSIONS FROM UACL - CLASS UB COMBUSTOR OVER SIMULATED FEDERAL DRIVING CYCLE (ZERO HUMIDITY)



FUEL JP4
VE = 8.6 mpg

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FIGURE 4.19 SUMMARY OF CLASS UB EMISSION RESULTS - NO_x VS CO EMISSION INDICES - AIR-ASSIST NOZZLE

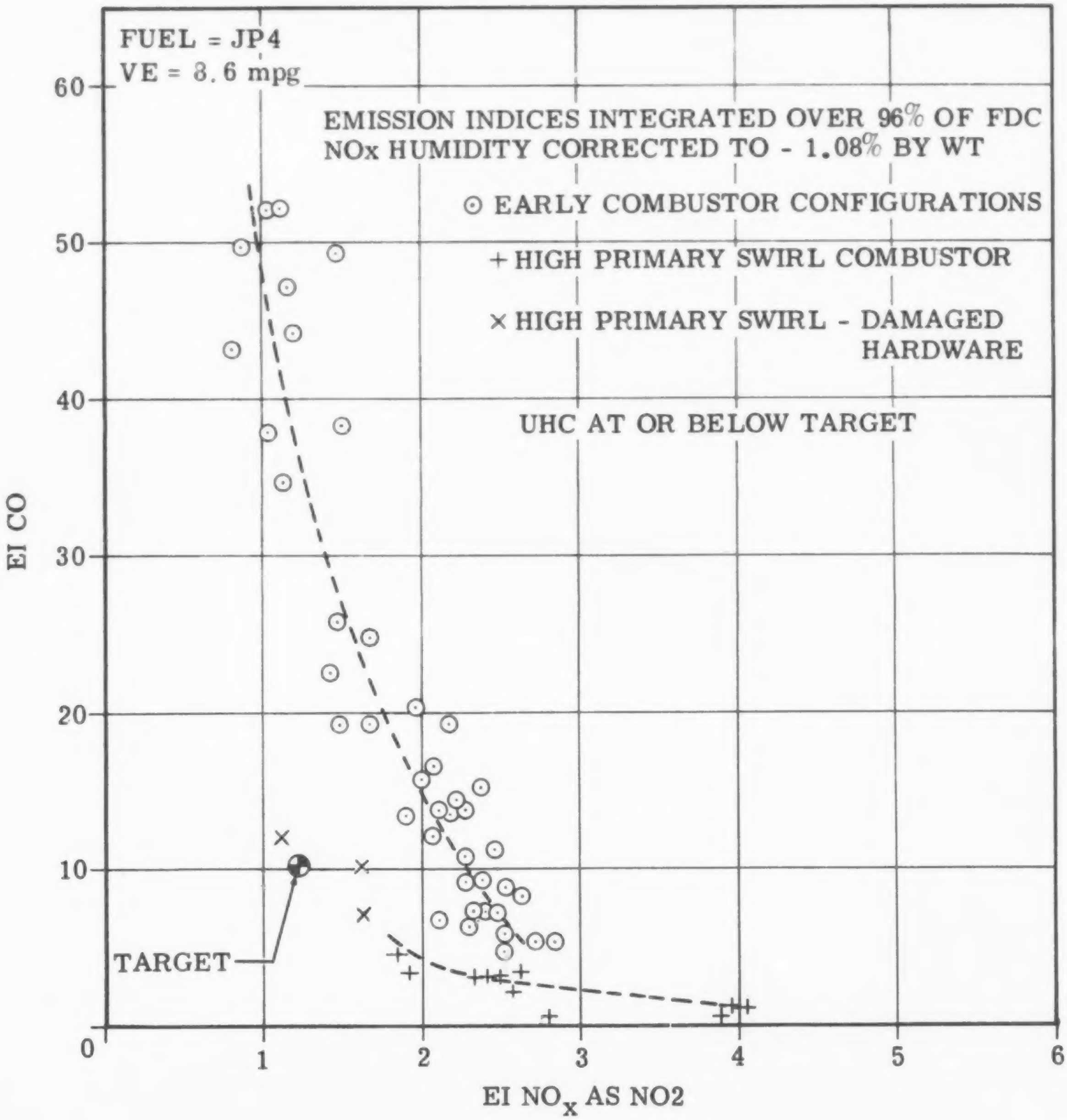

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FIGURE 4.20 SUMMARY OF CLASS UB EMISSION RESULTS - NO_x VS CO EMISSION INDICES - AIR-BLAST NOZZLE

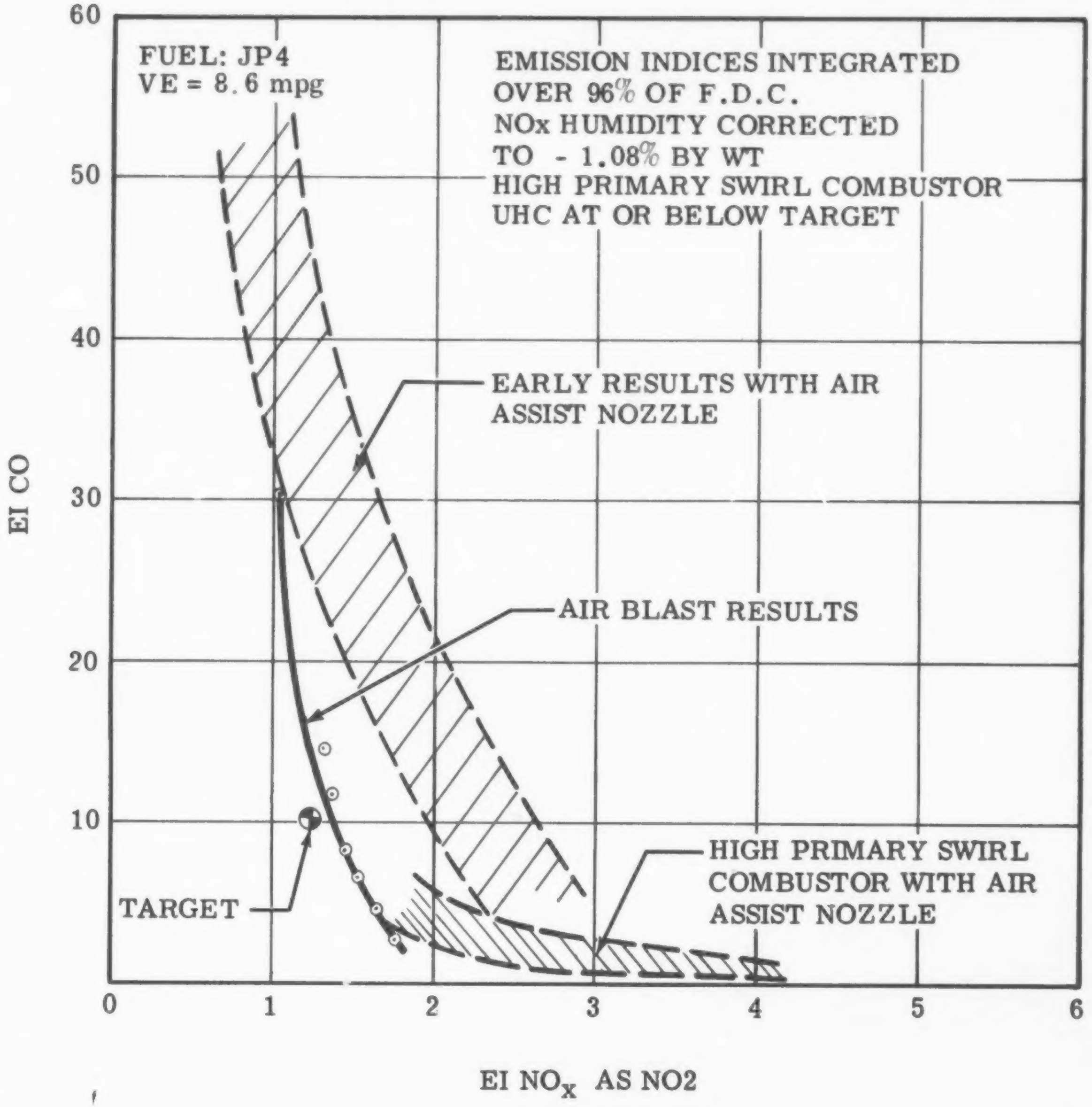

FIGURE 4.21 CLASS UB COMBUSTOR - FINAL CONFIGURATION

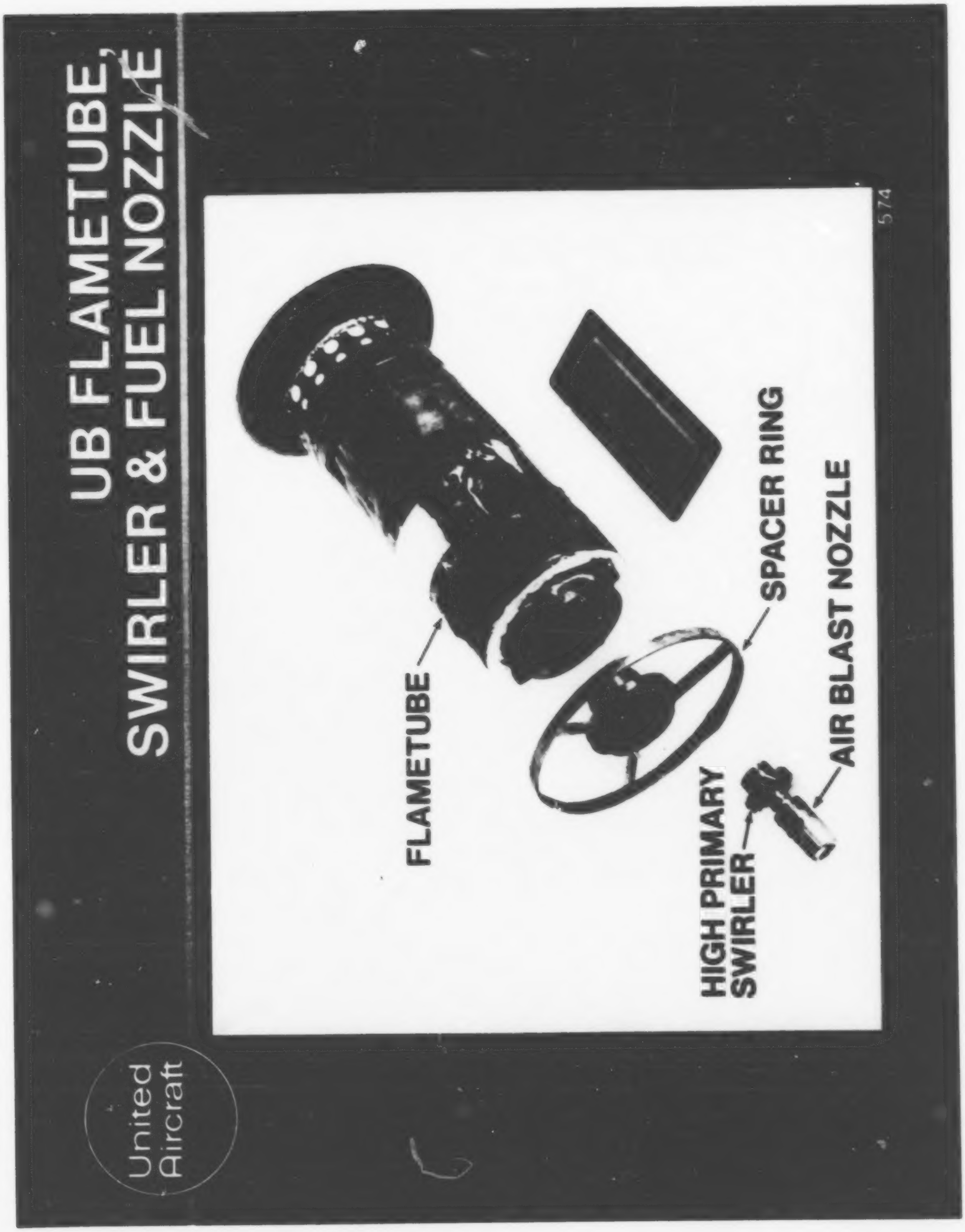
UB FLAMETUBE, SWIRLER & FUEL NOZZLE
FLAMETUBE
SPACER RING
AIR BLAST NOZZLE
HIGH PRIMARY SWIRLER
574
United Aircraft

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FIGURE 4.22 CROSS SECTION OF CLASS UB COMBUSTOR - FINAL CONFIGURATION

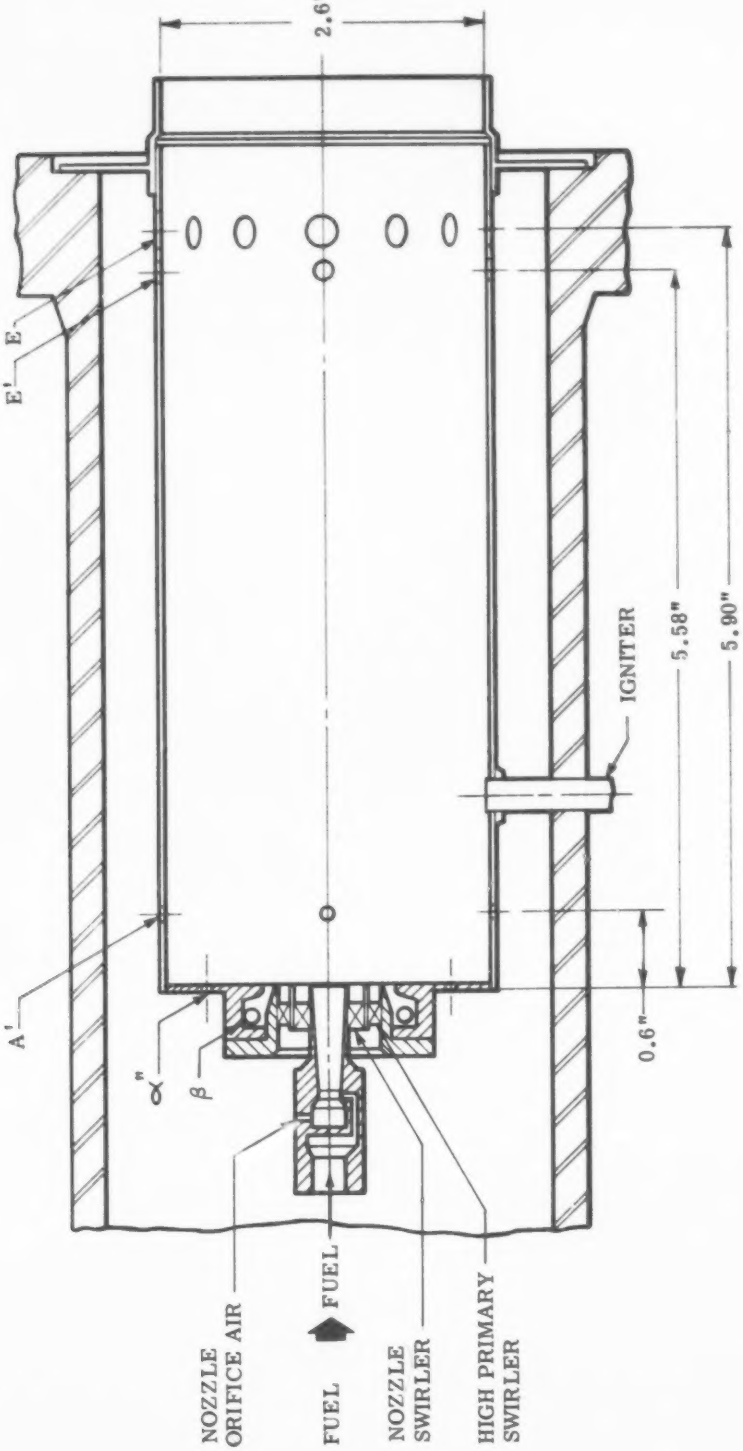
2.6"
E
E'
A'
α"
β
IGNITER
5.58"
5.90"
0.6"
NOZZLE ORIFICE AIR
FUEL
FUEL
NOZZLE SWIRLER
HIGH PRIMARY SWIRLER

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FIGURE 4.23 SCHEMATIC OF HUMIDITY TEST SET-UP

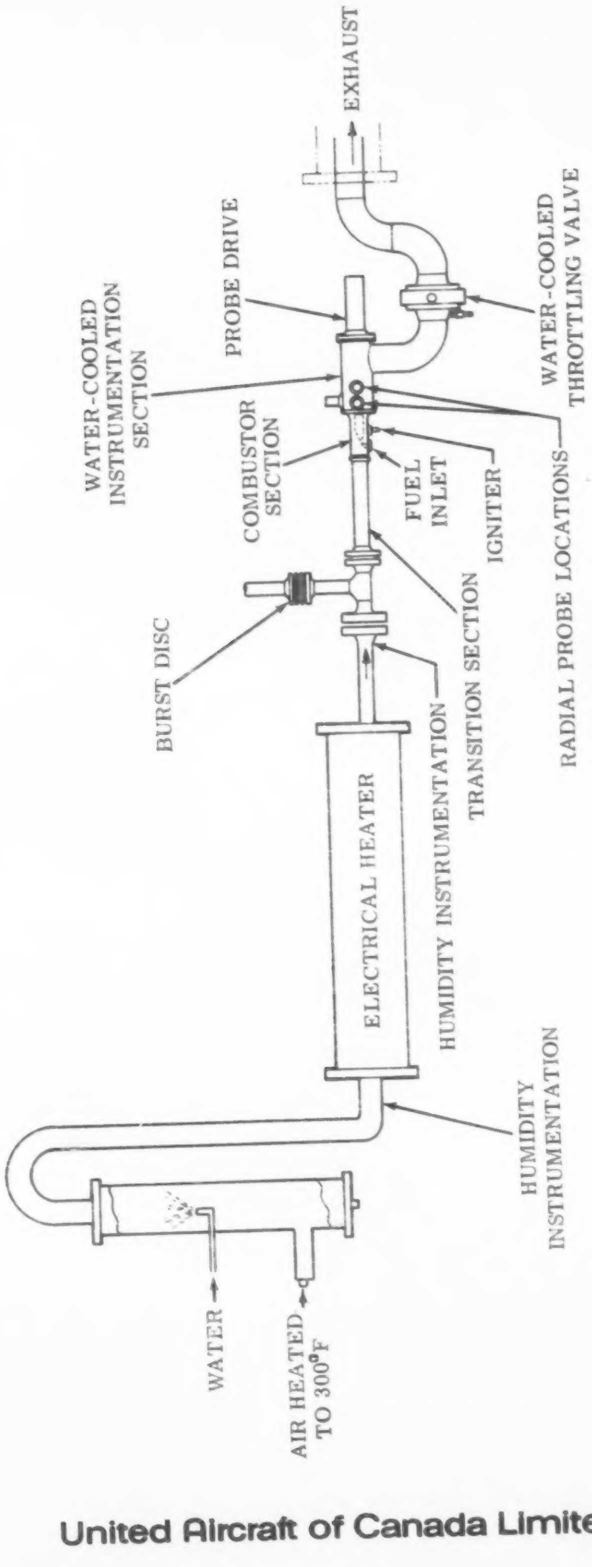
EXHAUST
PROBE DRIVE
WATER-COOLED INSTRUMENTATION SECTION
WATER-COOLED THROTTLING VALVE
COMBUSTOR SECTION
FUEL INLET
IGNITER
RADIAL PROBE LOCATIONS
BURST DISC
TRANSITION SECTION
HUMIDITY INSTRUMENTATION
ELECTRICAL HEATER
HUMIDITY INSTRUMENTATION
WATER
AIR HEATED TO 300°F

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FIGURE 4.24 EFFECT OF HUMIDITY ON NO_x EMISSIONS

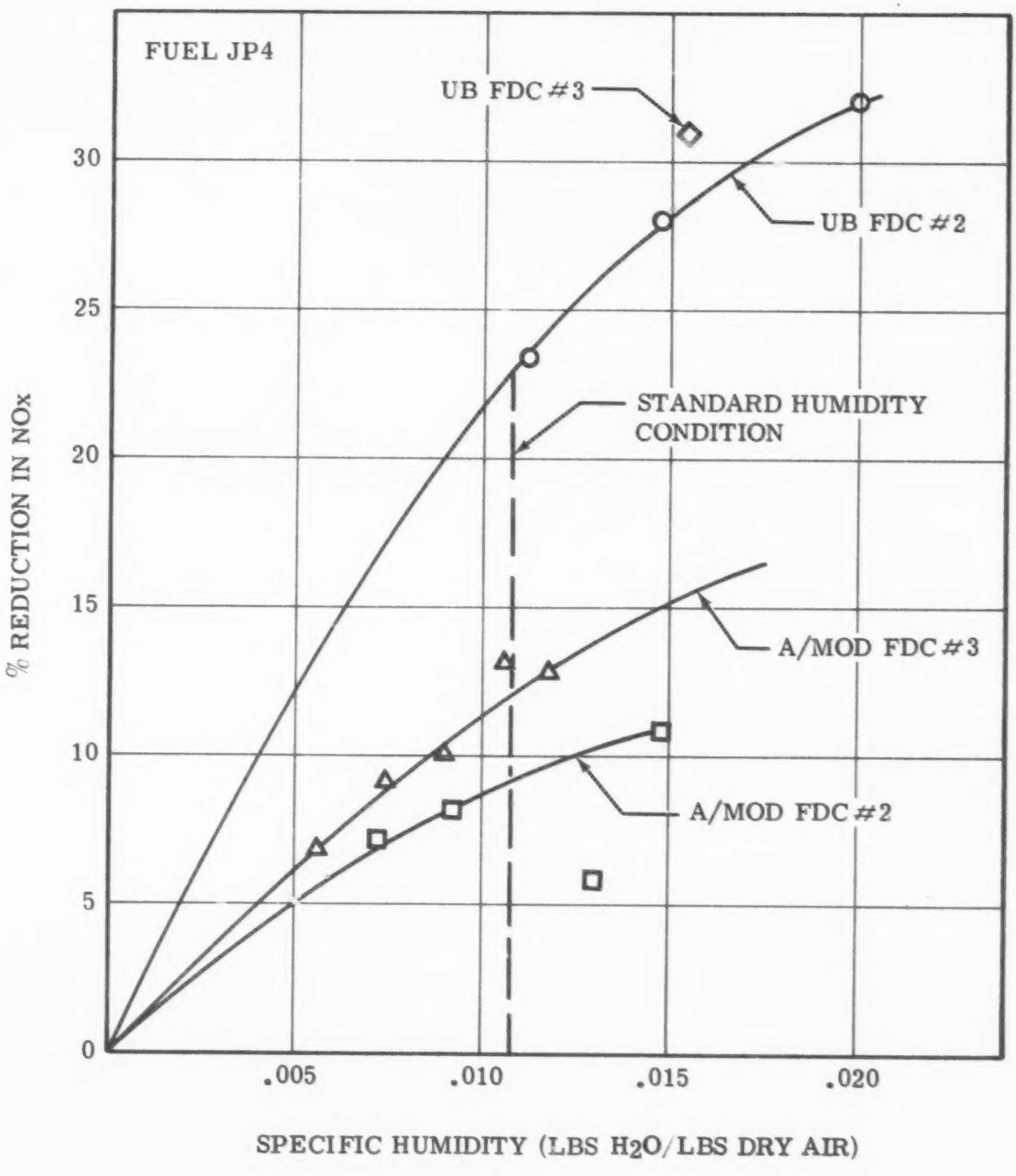

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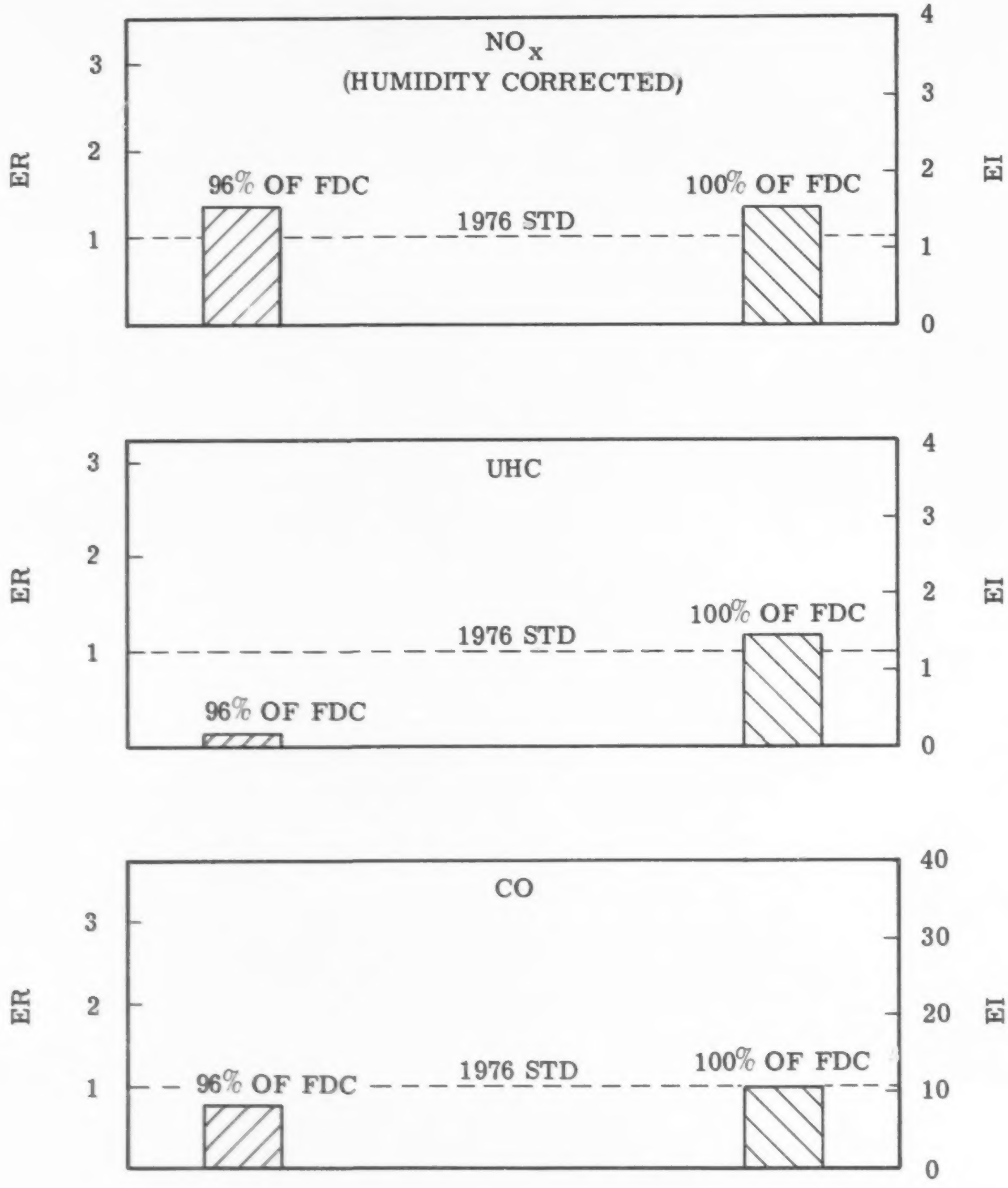
FIGURE 4.25 CLASS UB COMBUSTOR EMISSIONS OVER SIMULATED FEDERAL DRIVING CYCLE (HUMIDITY CORRECTED)



FUEL: JP4

VE = 8.6 mpg

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FIGURE 4.26 CLASS UB COMBUSTOR EMISSIONS IN STEADY SPEED OPERATION (ZERO HUMIDITY)

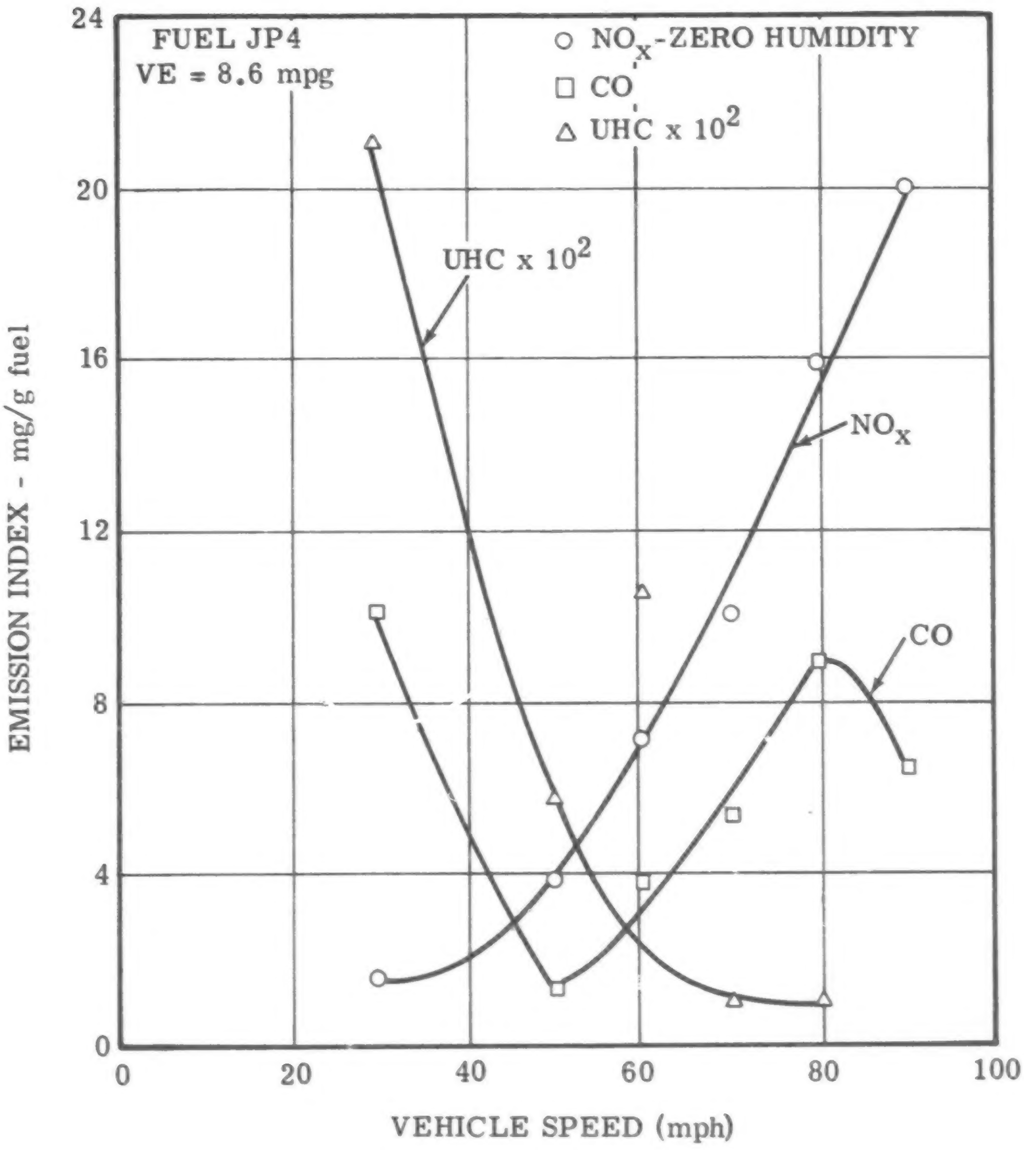

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FIGURE 4.27 CLASS UB COMBUSTOR EMISSIONS IN STEADY SPEED OPERATION (HUMIDITY CORRECTED)

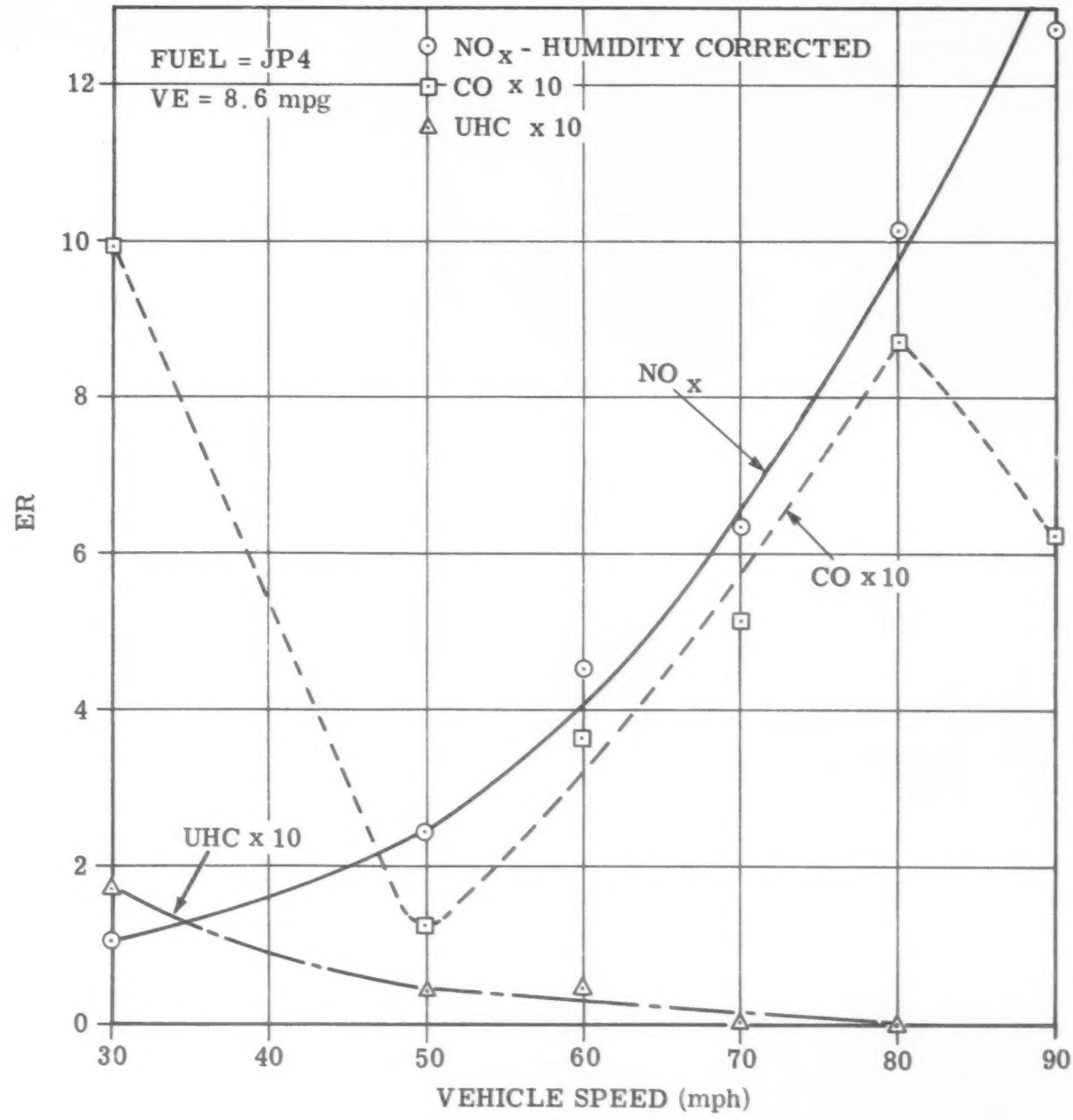

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FIGURE 4.28 CLASS UB COMBUSTOR EMISSIONS IN STEADY SPEED OPERATION - EFFECT OF FUEL FLOW RATE

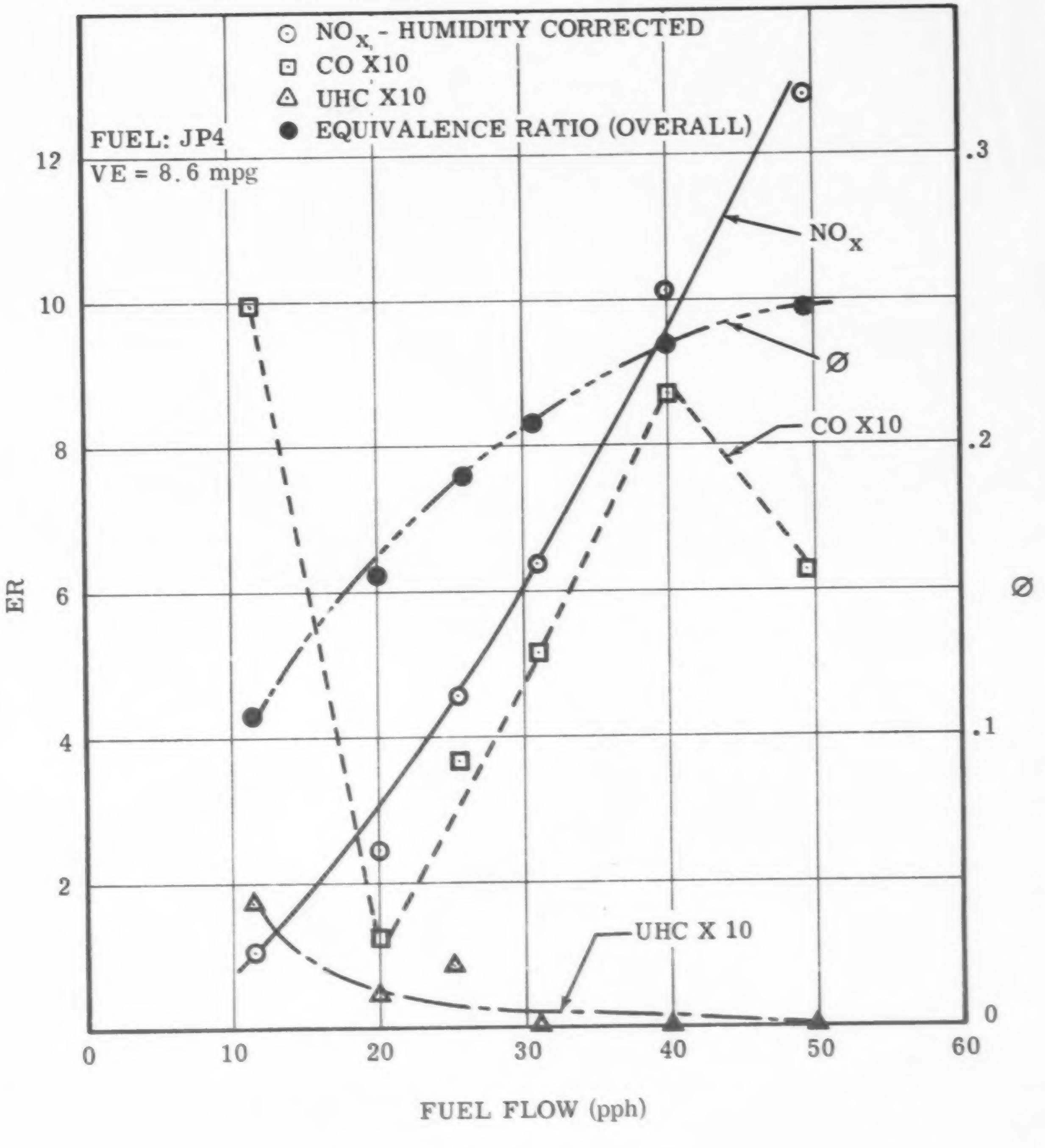

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FIGURE 4.29 CLASS UB COMBUSTOR EMISSIONS IN STEADY SPEED OPERATION - EFFECT OF SHP

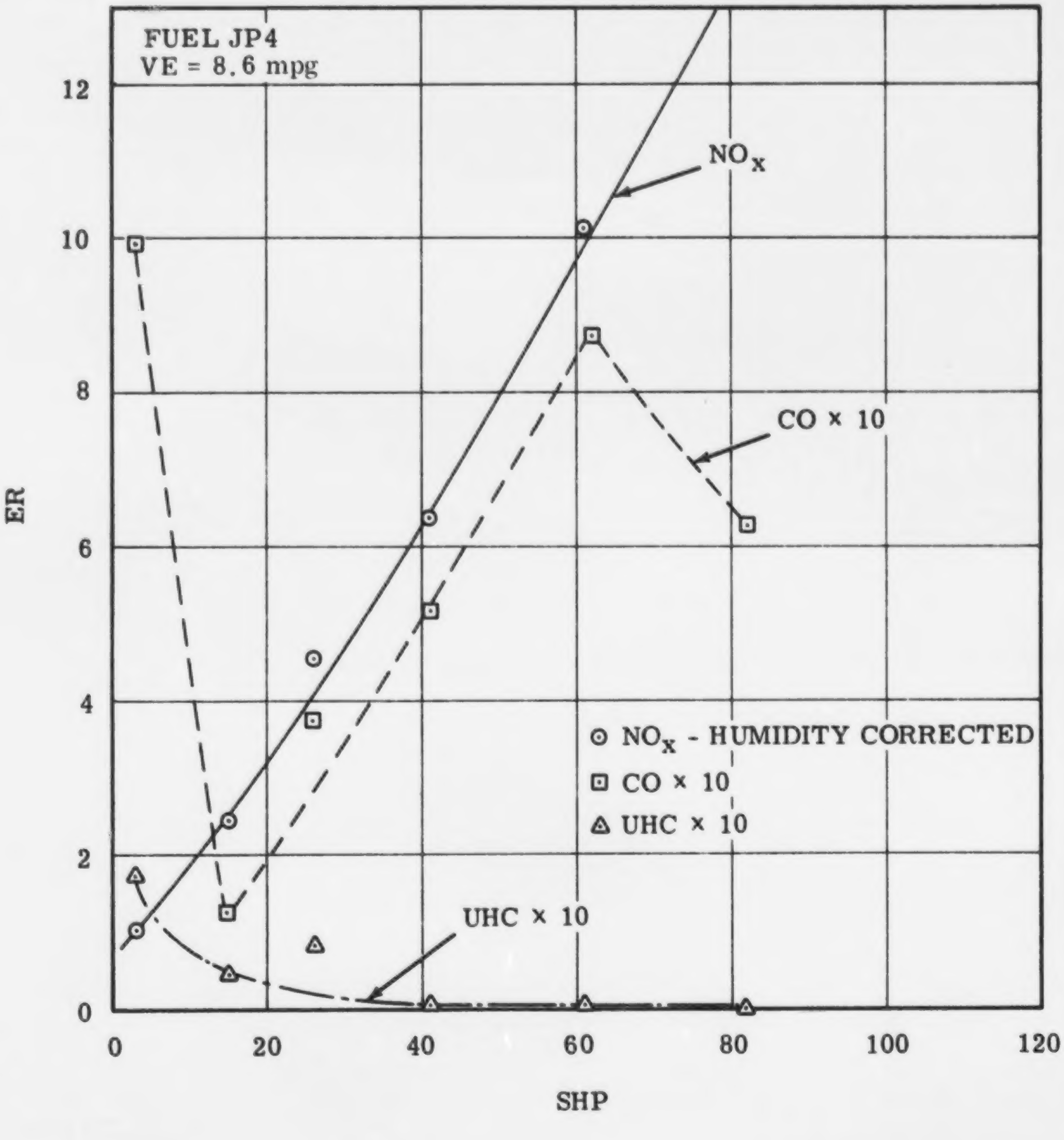

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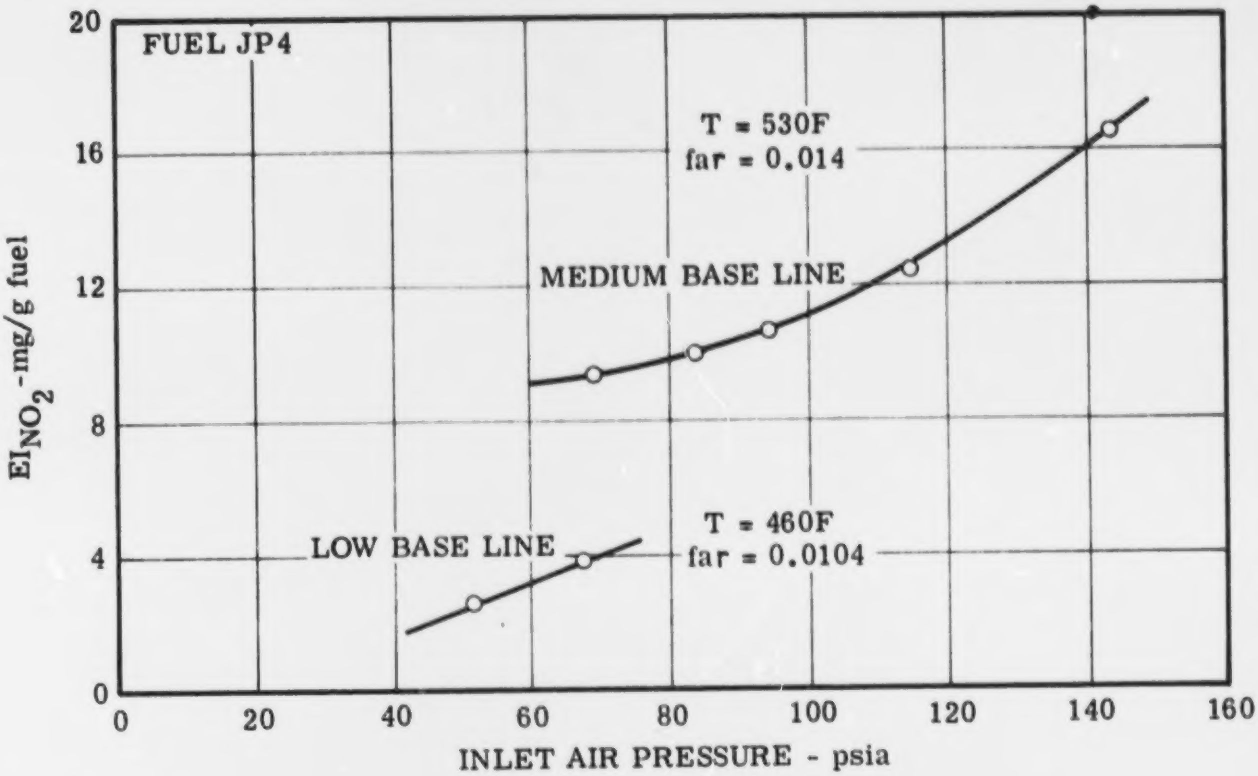
FIGURE 4.30 CLASS UB COMBUSTOR EMISSIONS IN RANGE MODE OPERATION - PRESSURE EFFECT (ZERO HUMIDITY)



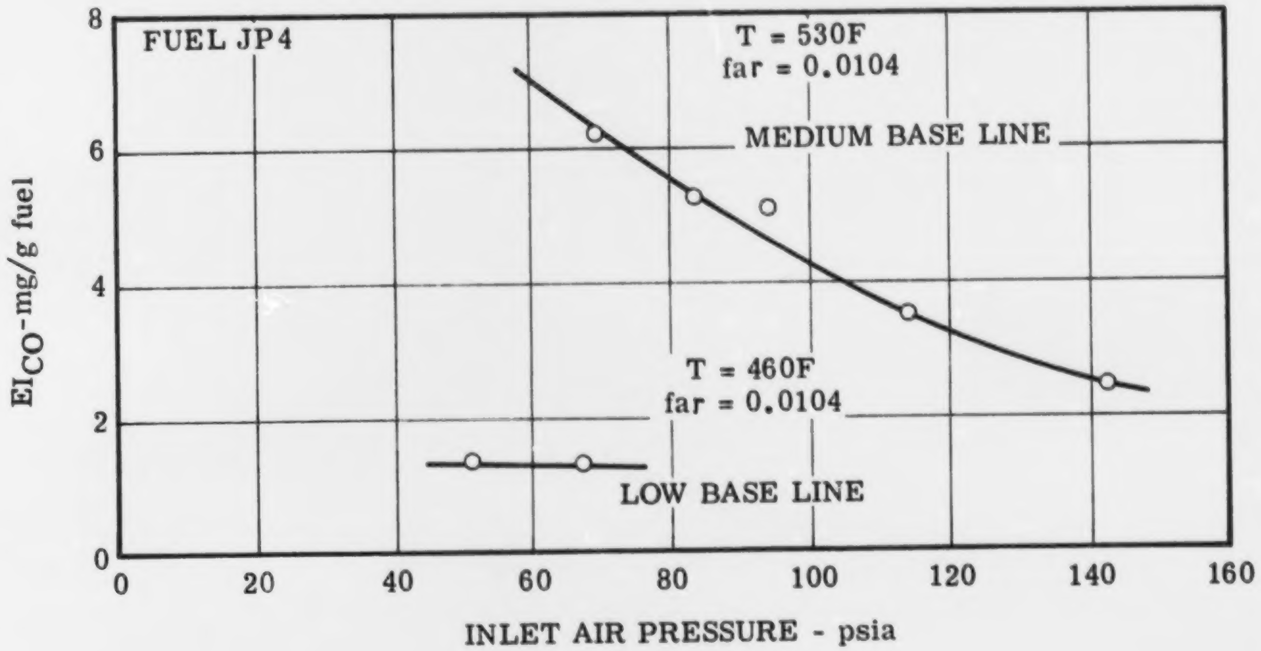


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FIGURE 4.31 CLASS UB COMBUSTOR EMISSIONS IN RANGE MODE OPERATION - TEMPERATURE EFFECT (ZERO HUMIDITY)

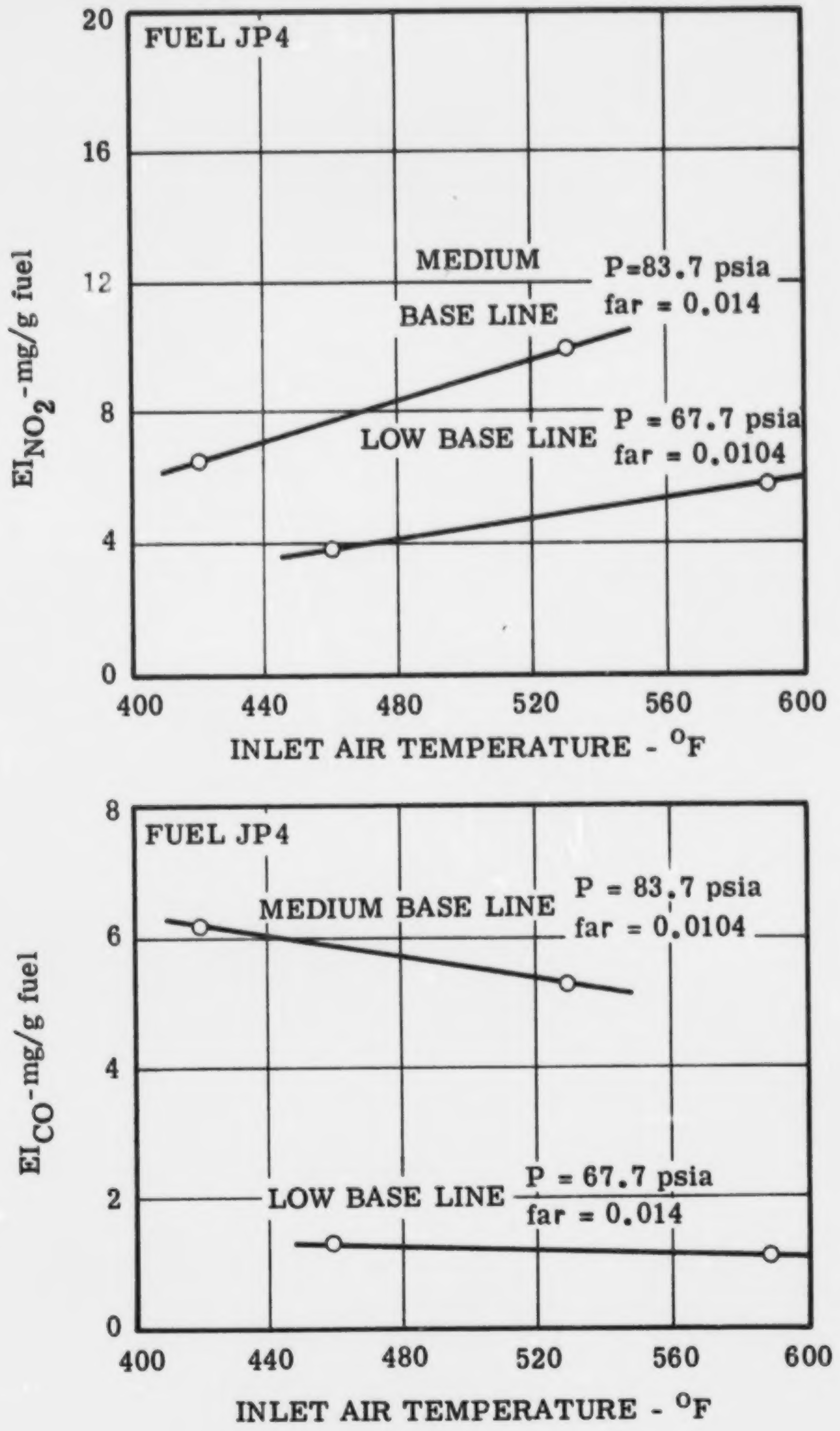

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FIGURE 4.32 CLASS UB COMBUSTOR EMISSIONS IN RANGE MODE OPERATION - LOW BASE LINE CONDITION (HUMIDITY CORRECTED)

CONDITION	P_{IN} (PSIA)	T_{IN} ^oF	far	EMISSION INDICES			EMISSION RATIO			CODE
				UHC	CO	NOx	UHC	CO	NOx	
LOW BASE LINE (50 MPH)	67.7	460	0.0104	.057	1.30	2.91	.047	.127	2.466	▩
PRESS. CHANGE	51.7	460	0.0104	.112	1.34	1.85	.092	.1313	1.568	▨
TEMP. CHANGE	67.7	590	0.0104	.089	1.11	4.3	0.73	.1089	3.644	▧

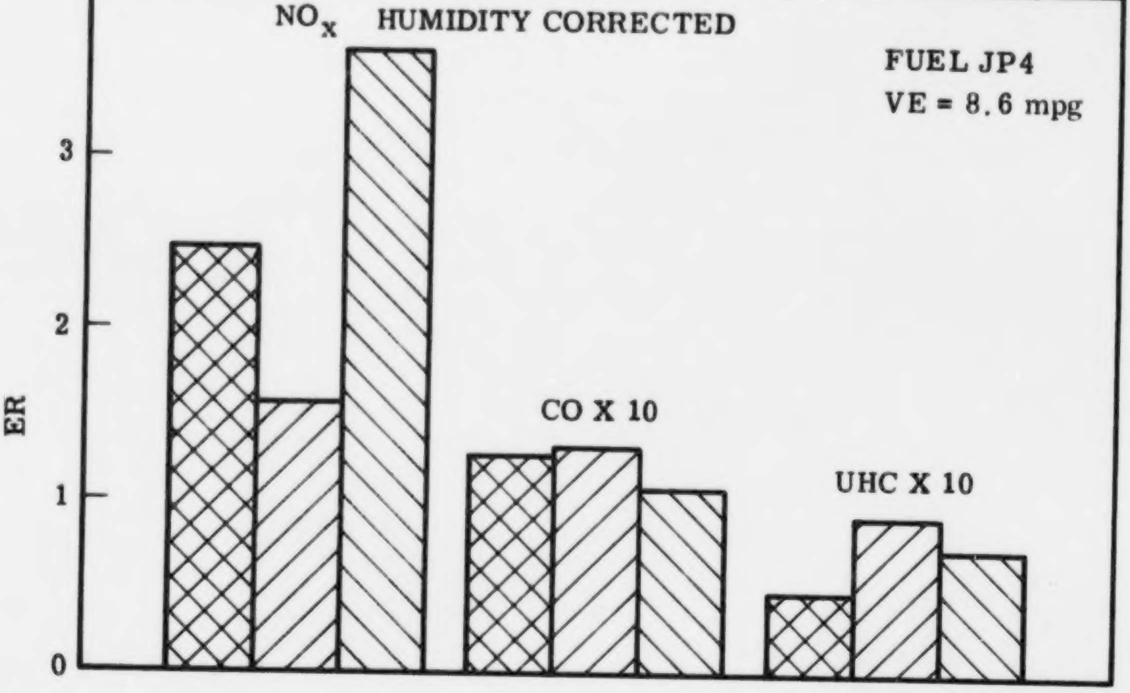

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FIGURE 4.33 CLASS UB COMBUSTOR EMISSIONS IN RANGE MODE OPERATION - MEDIUM BASE LINE CONDITION. PRESSURE EFFECT (HUMIDITY CORRECTED)

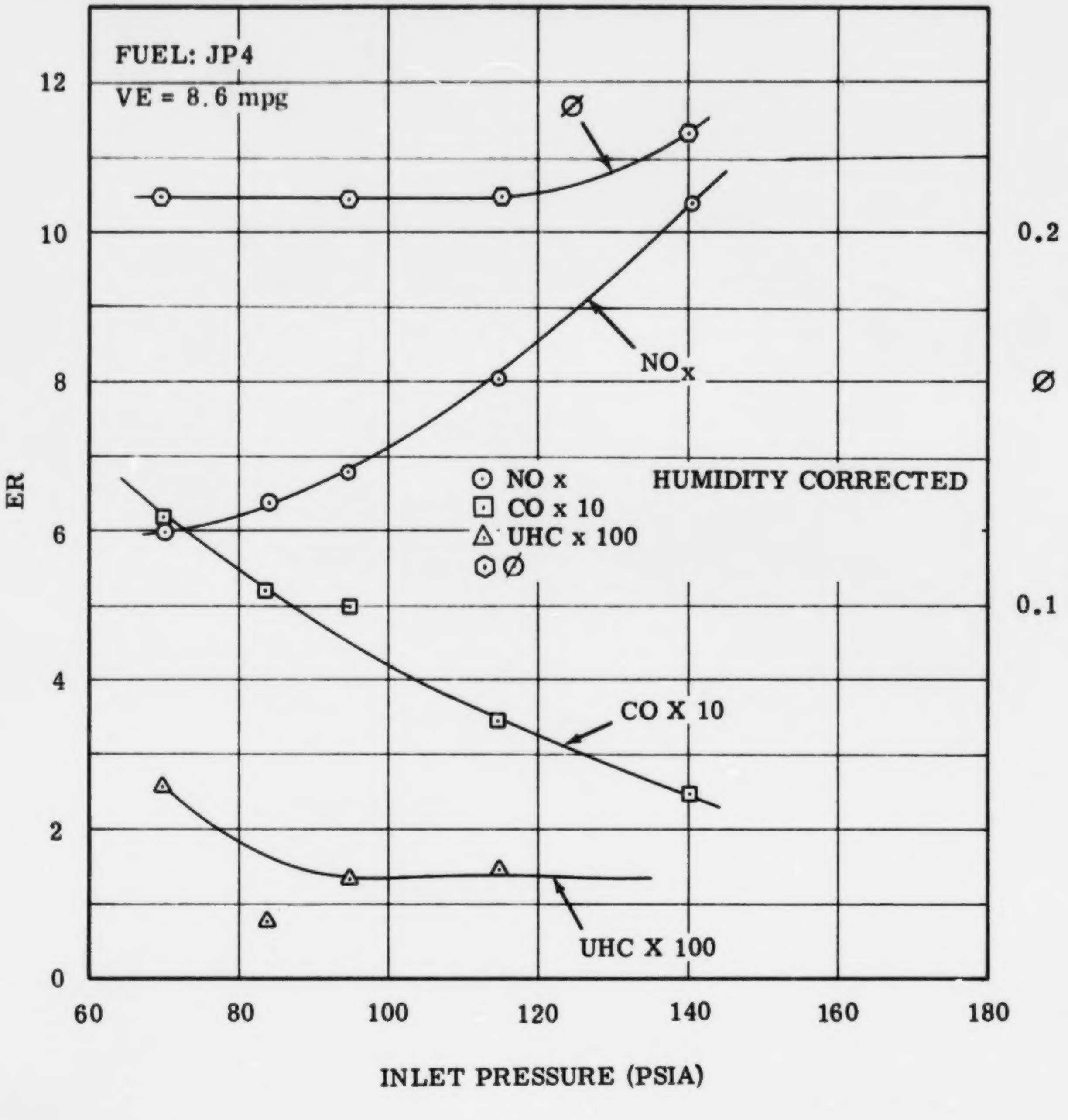

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FIGURE 4.34 CLASS UB COMBUSTOR EMISSIONS IN RANGE MODE OPERATION - MEDIUM BASE LINE CONDITION. TEMPERATURE EFFECT (HUMIDITY CORRECTED)

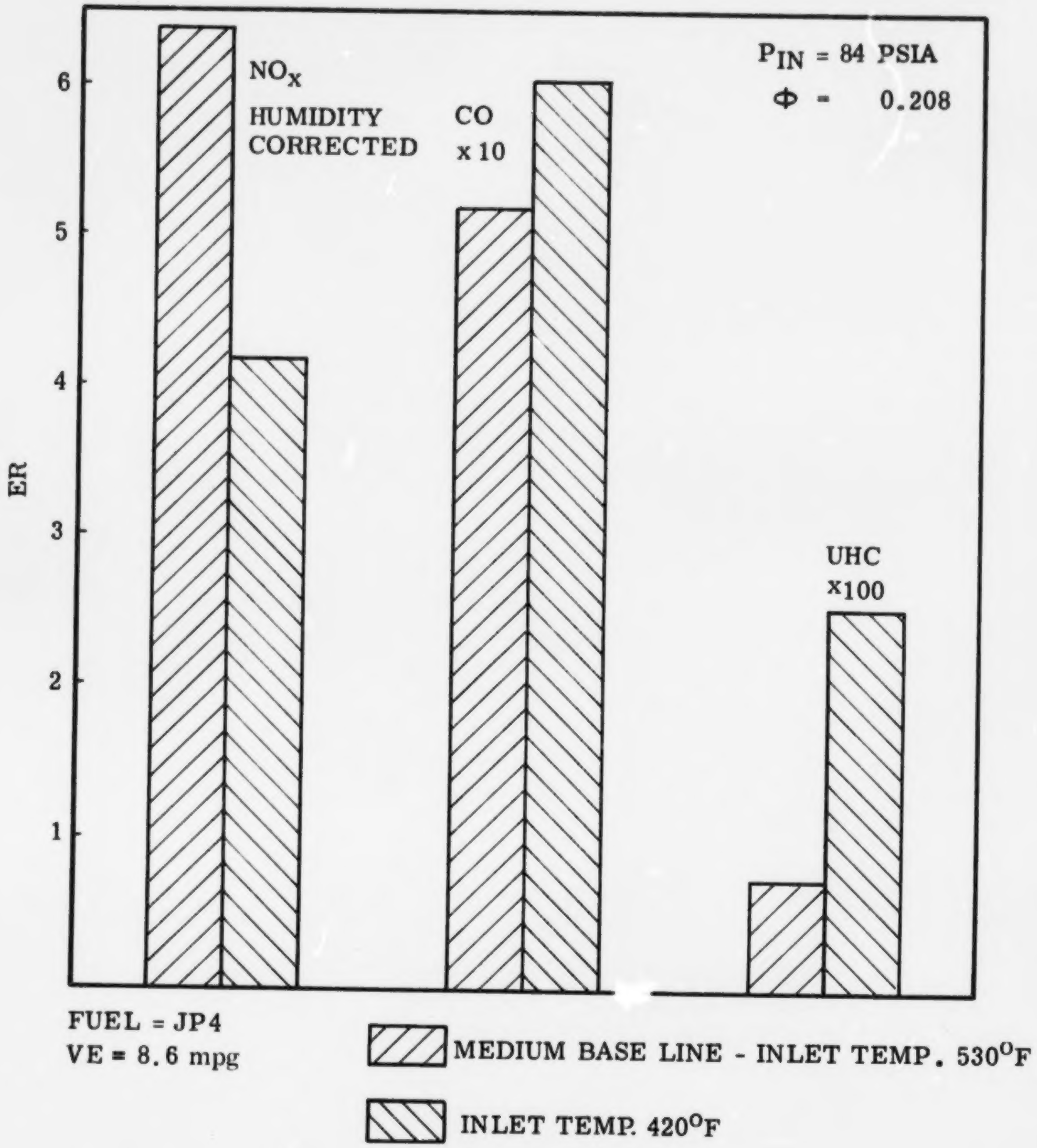

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FIGURE 4.35 COMBUSTOR ASSEMBLY - A/MOD

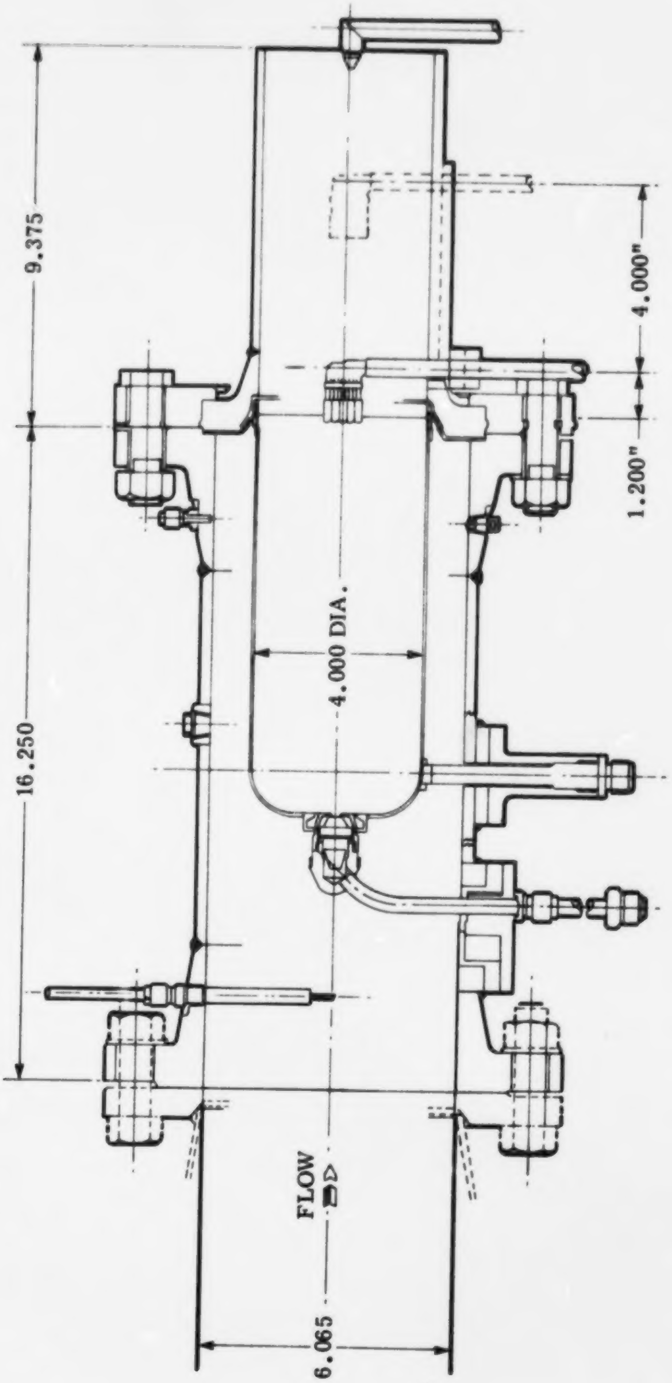
9.375
16.250
4.000"
1.200"
4.000 DIA.
FLOW
6.065

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FIGURE 4.36 CLASS A/MOD COMBUSTOR - INITIAL DESIGN

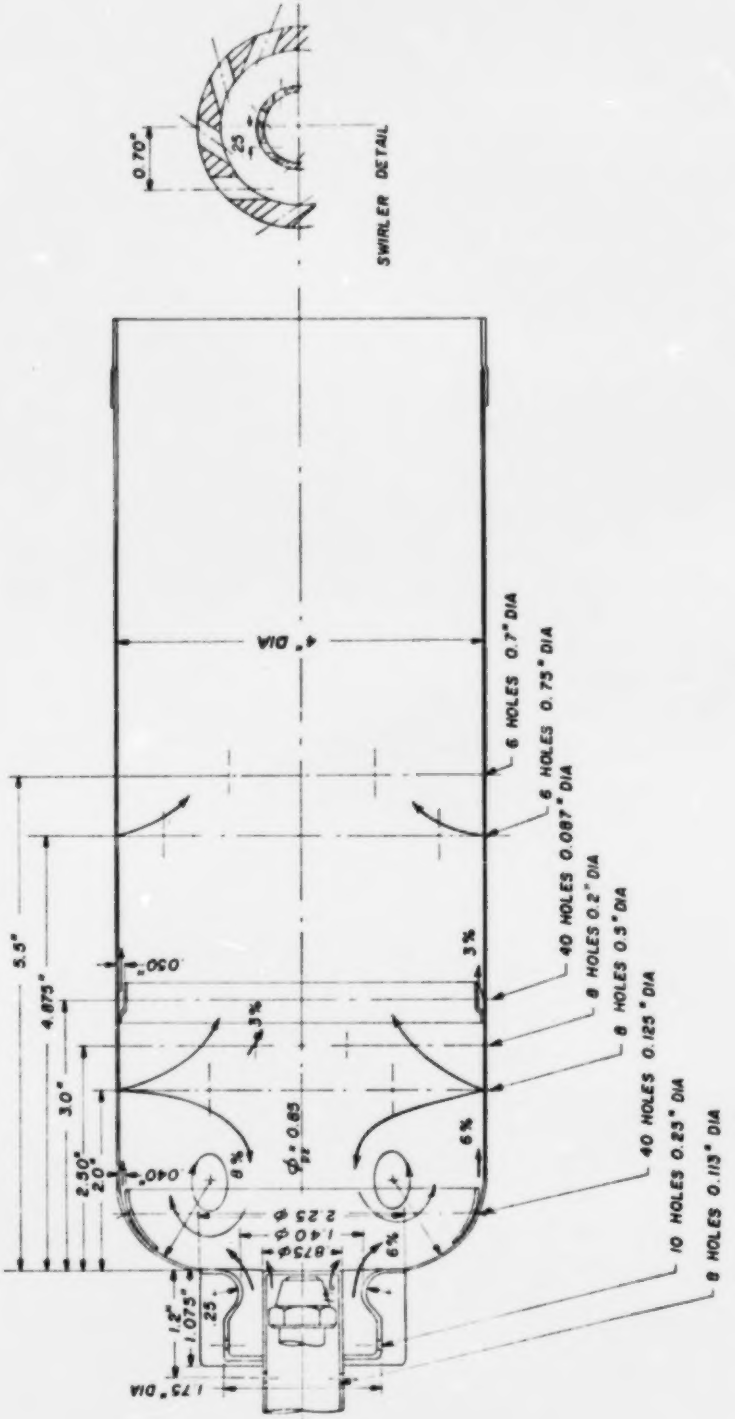
0.70"
.25
SWIRLER DETAIL
4" DIA
6 HOLES 0.7" DIA
6 HOLES 0.75" DIA
40 HOLES 0.087" DIA
8 HOLES 0.2" DIA
8 HOLES 0.3" DIA
8 HOLES 0.125" DIA
40 HOLES 0.25" DIA
10 HOLES 0.113" DIA
8 HOLES
5.5"
4.875"
3.0"
2.50"
2.0"
.050"
.040"
3%
3%
8%
6%
6%
Φ = 0.85
2.25 Φ
1.40 Φ
.875 Φ
1.2"
1.075"
.25
1.75" DIA

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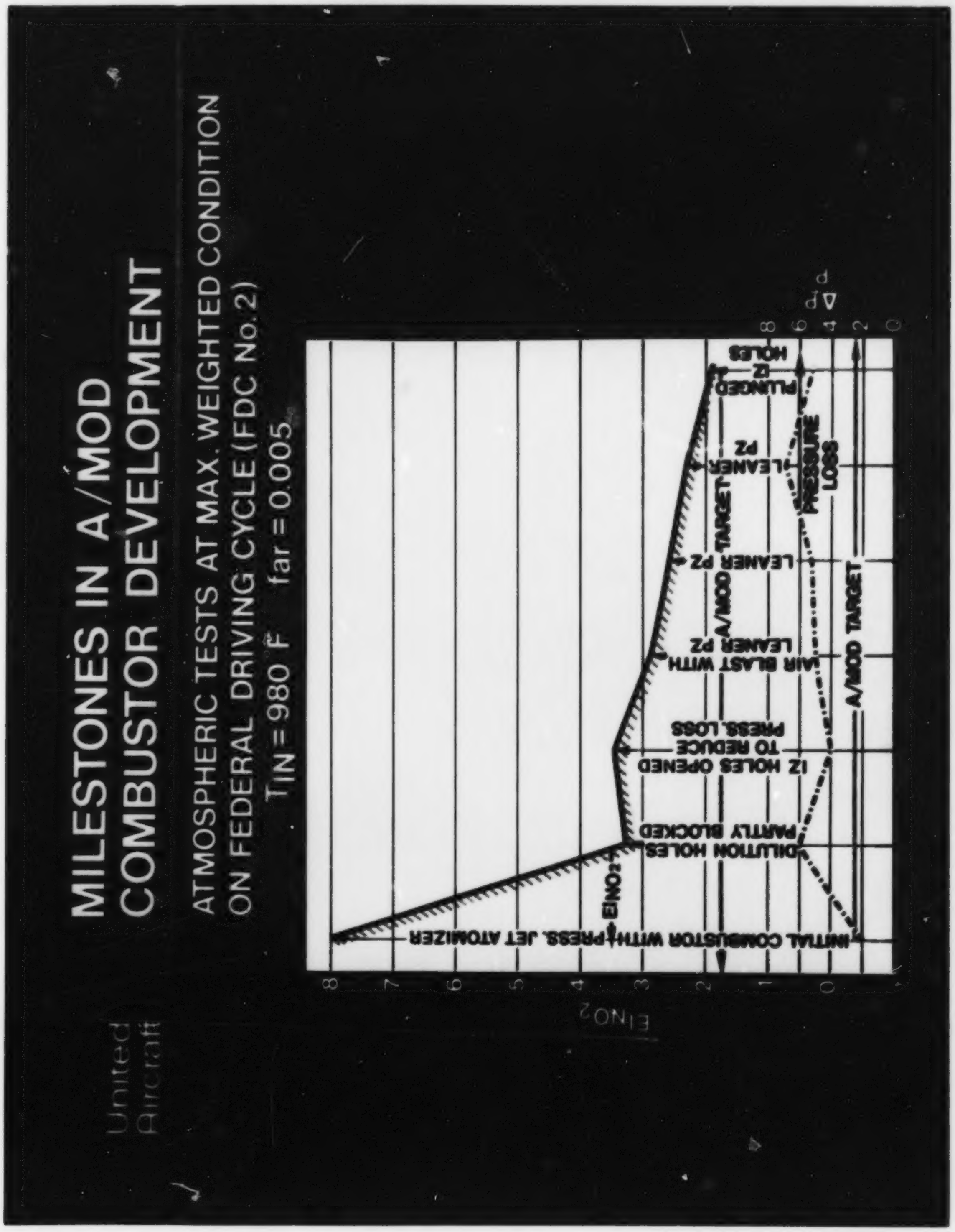
FIGURE 4.37 MILESTONES IN CLASS A/MOD COMBUSTOR DEVELOPMENT (ATMOSPHERIC TESTS AT UACL)



MILESTONES IN A/MOD COMBUSTOR DEVELOPMENT

ATMOSPHERIC TESTS AT MAX. WEIGHTED CONDITION ON FEDERAL DRIVING CYCLE (FDC No.2)

$T_{IN} = 980°F$ far = 0.005

United Aircraft

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FIGURE 4.38 SUMMARY OF CLASS A/MOD EMISSION RESULTS - NO_x VS CO EMISSION INDICES - AIR-BLAST NOZZLE

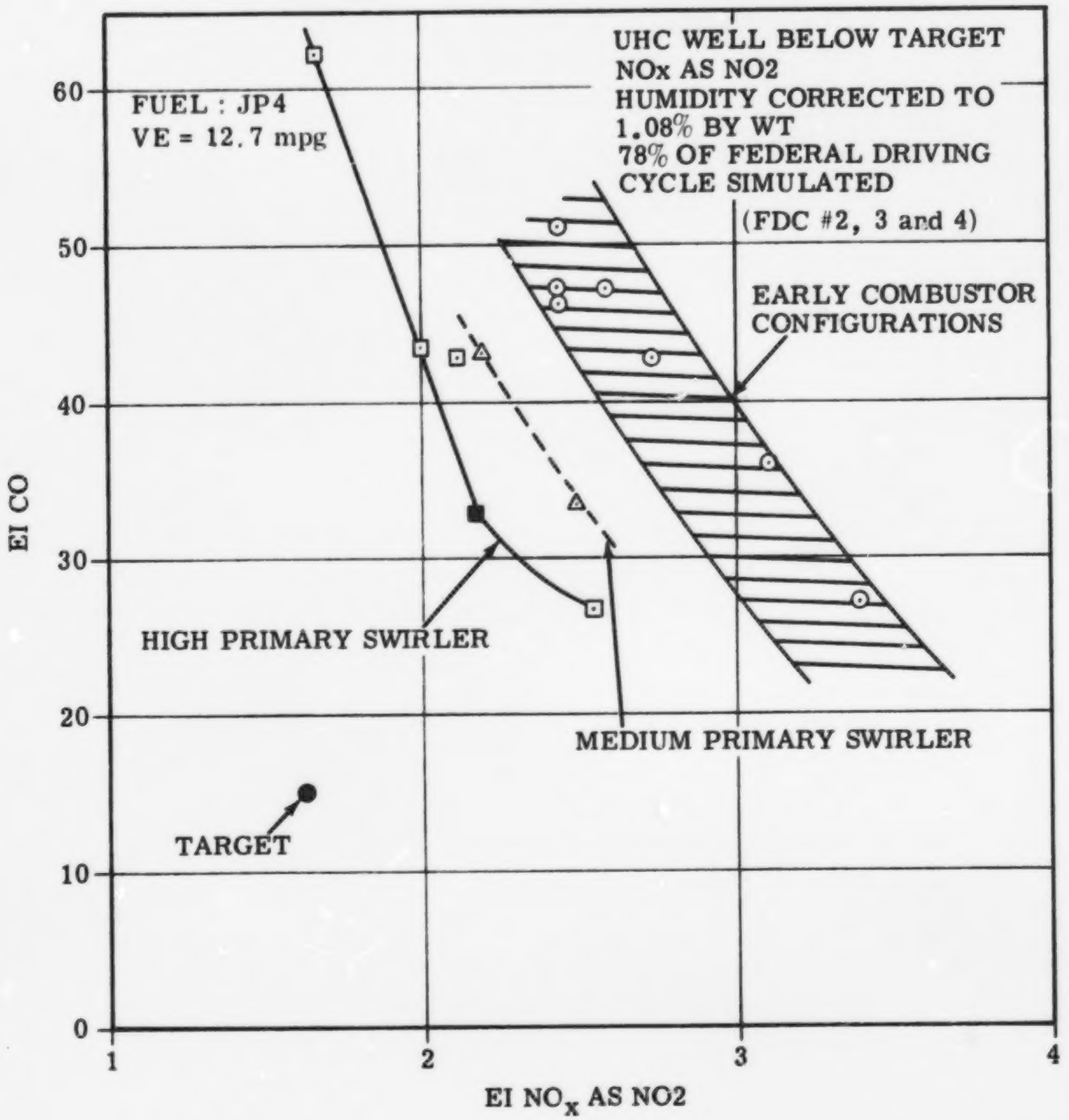

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FIGURE 4.39 CLASS A/MOD COMBUSTOR DURING DEVELOPMENT

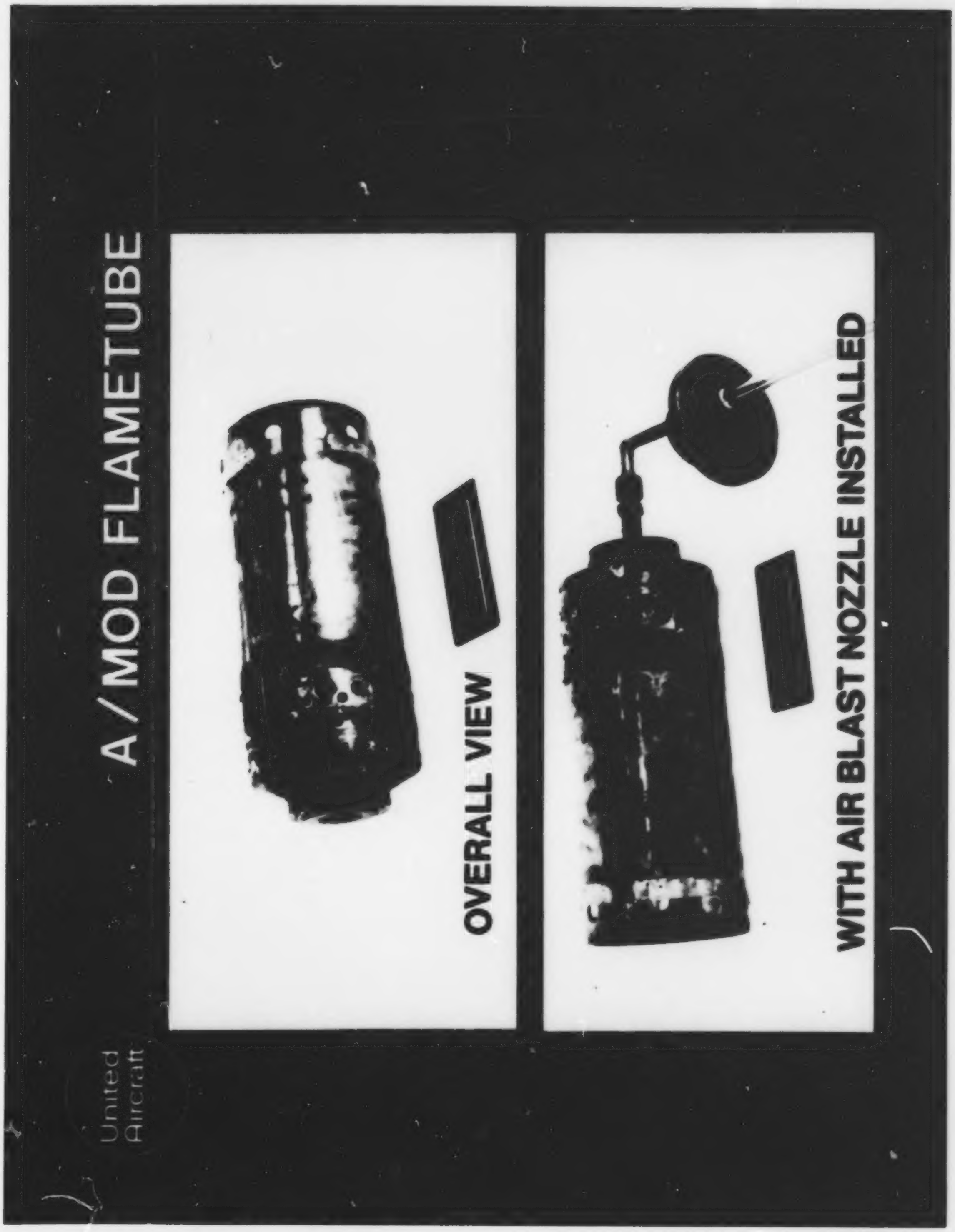
A / MOD FLAMETUBE
OVERALL VIEW
WITH AIR BLAST NOZZLE INSTALLED
United Aircraft

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FIGURE 4.40 CROSS SECTION OF CLASS A/MOD COMBUSTOR - FINAL CONFIGURATION

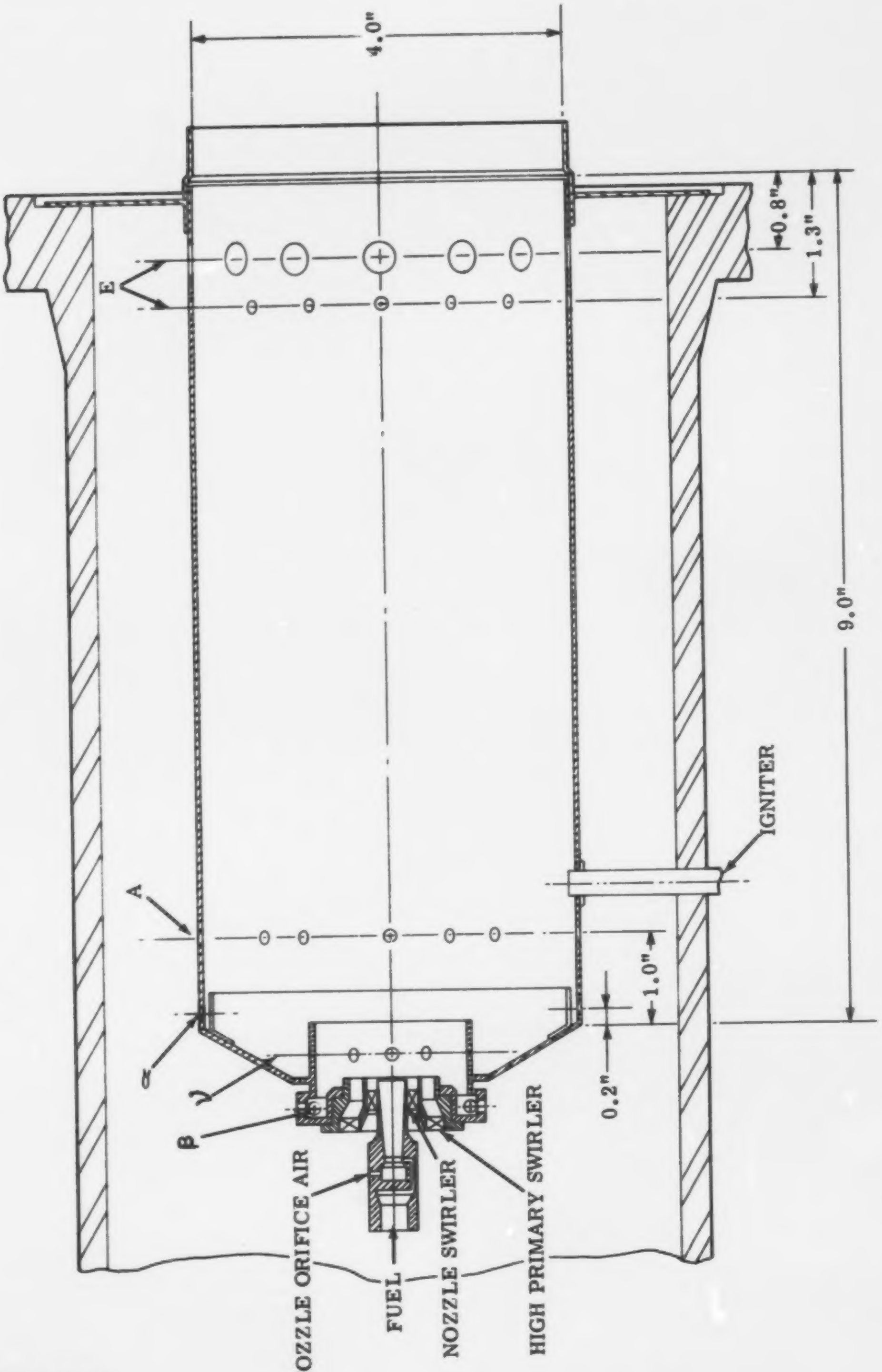
4.0"
0.8"
1.3"
9.0"
E
A
IGNITER
1.0"
0.2"
α
γ
β
NOZZLE ORIFICE AIR
FUEL
NOZZLE SWIRLER
HIGH PRIMARY SWIRLER

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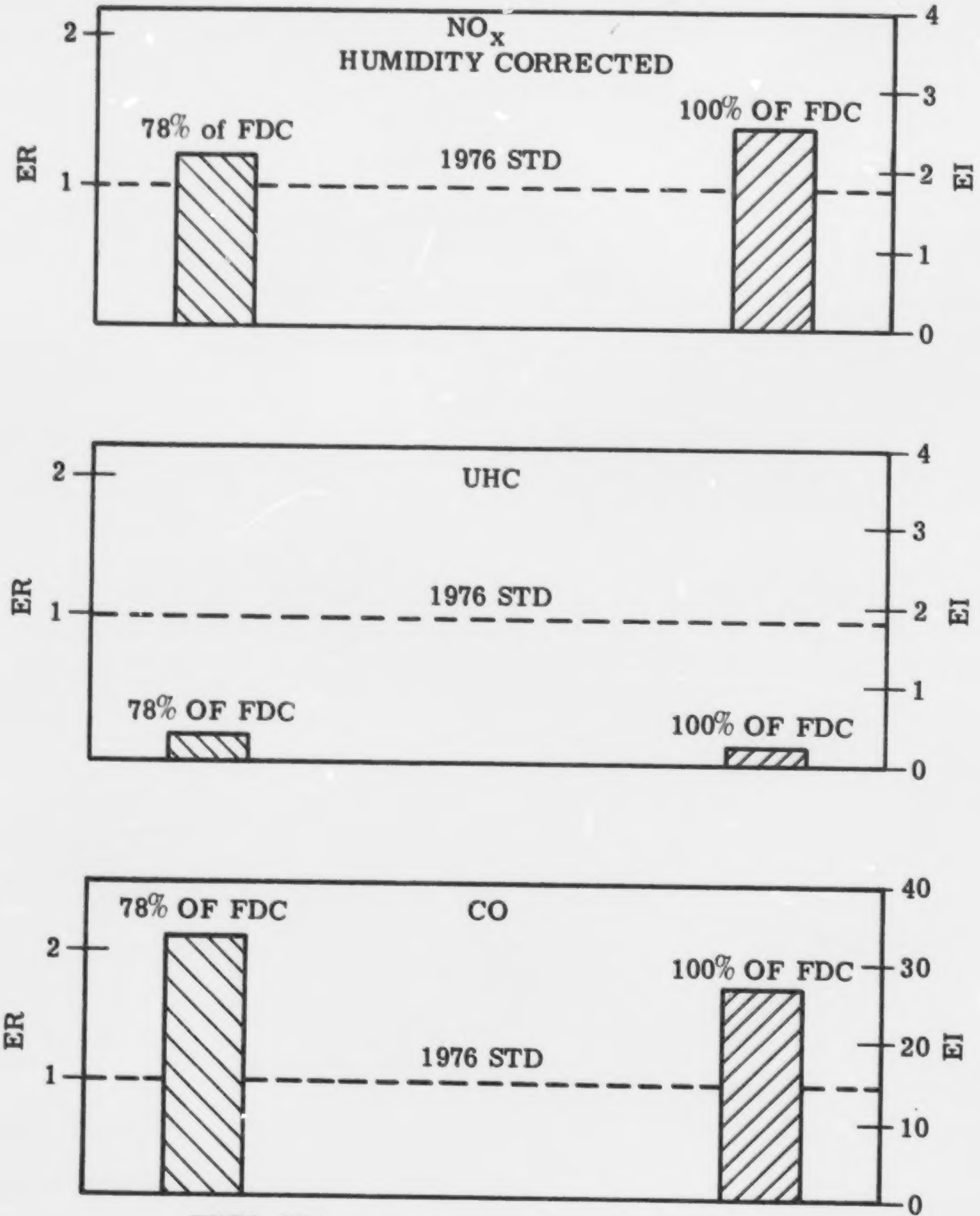
FIGURE 4.41 CLASS A/MOD COMBUSTOR EMISSIONS OVER SIMULATED FEDERAL DRIVING CYCLE (HUMIDITY CORRECTED)



FUEL JP4
VE = 12.7 mpg

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FIGURE 4.42 CLASS A/MOD COMBUSTOR EMISSIONS IN STEADY SPEED OPERATION - EFFECT OF VEHICLE SPEED (HUMIDITY CORRECTED)

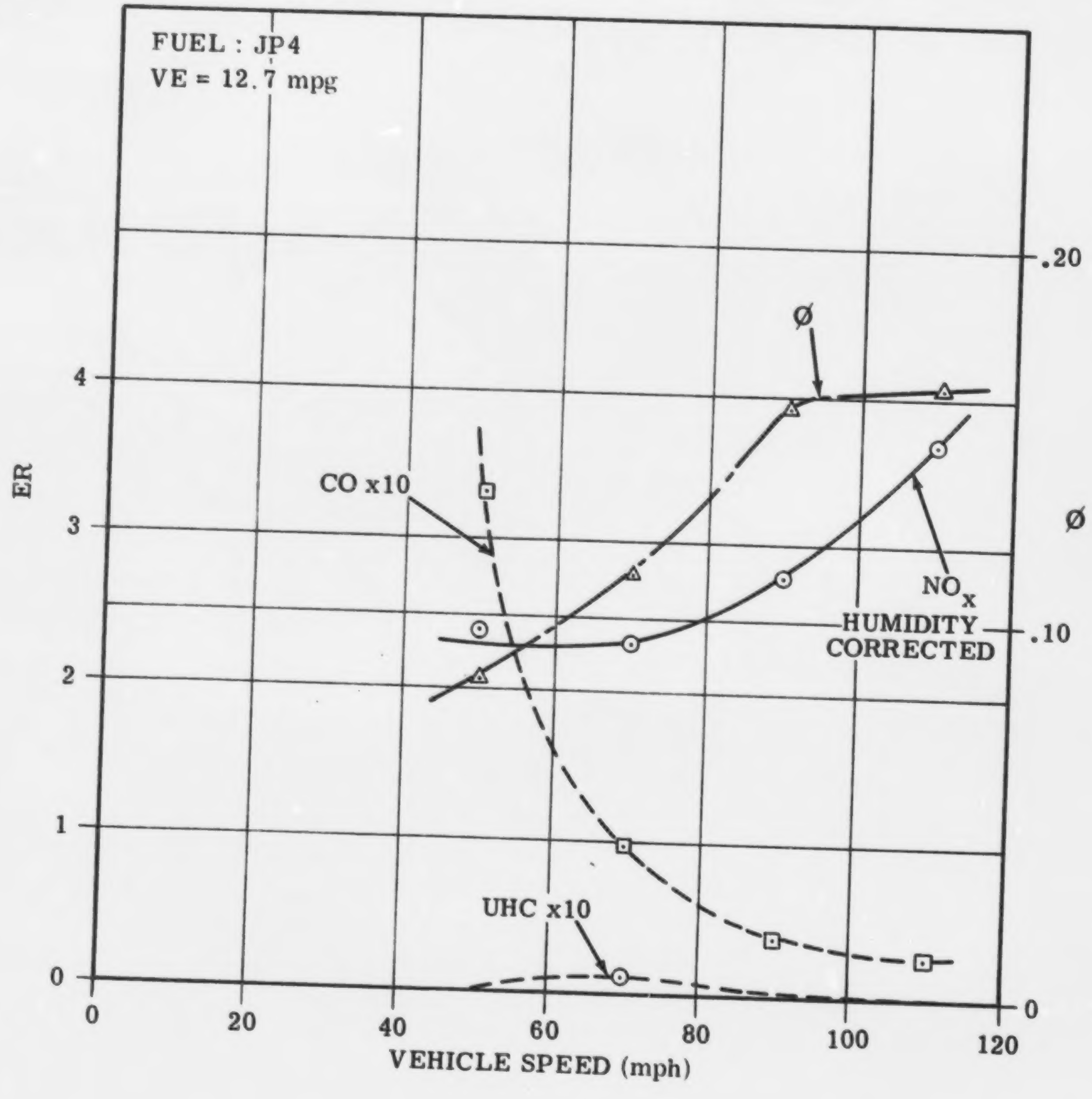

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FIGURE 4.43 CLASS A/MOD COMBUSTOR EMISSIONS IN STEADY SPEED OPERATION - EFFECT OF VEHICLE SPEED (ZERO HUMIDITY)

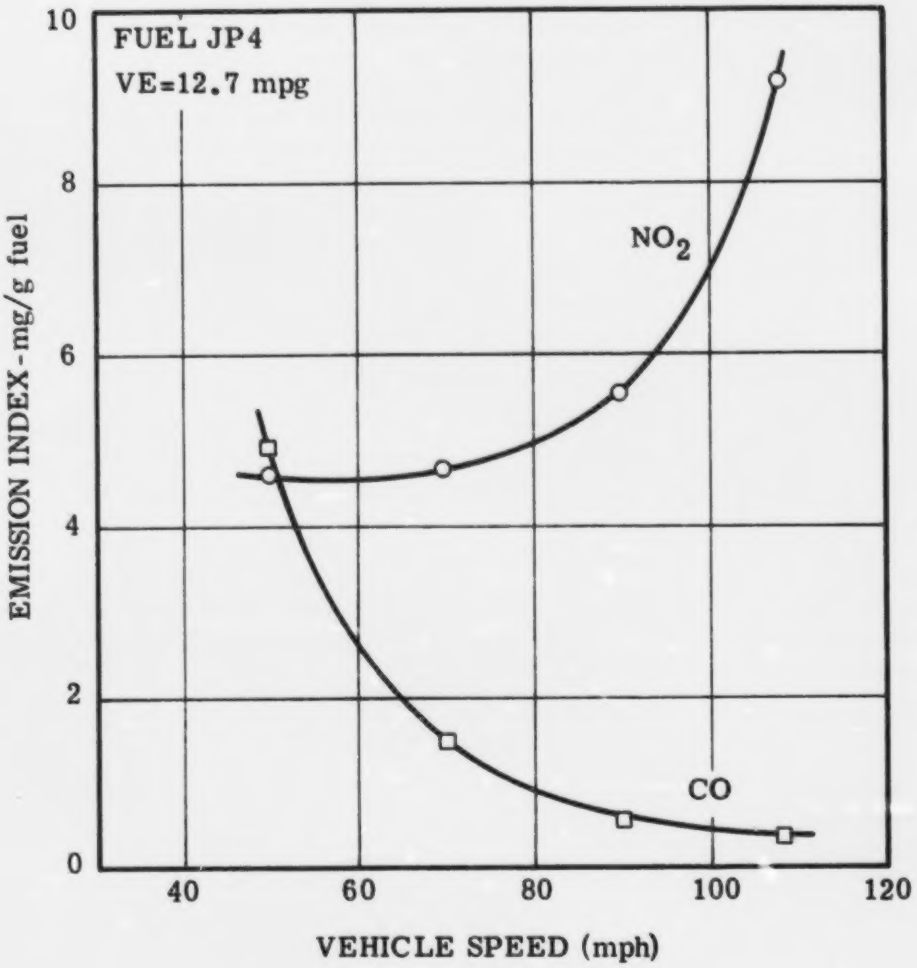

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FIGURE 4.44 CLASS A/MOD COMBUSTOR EMISSIONS IN STEADY SPEED OPERATION - EFFECT OF FUEL FLOW RATE (HUMIDITY CORRECTED)

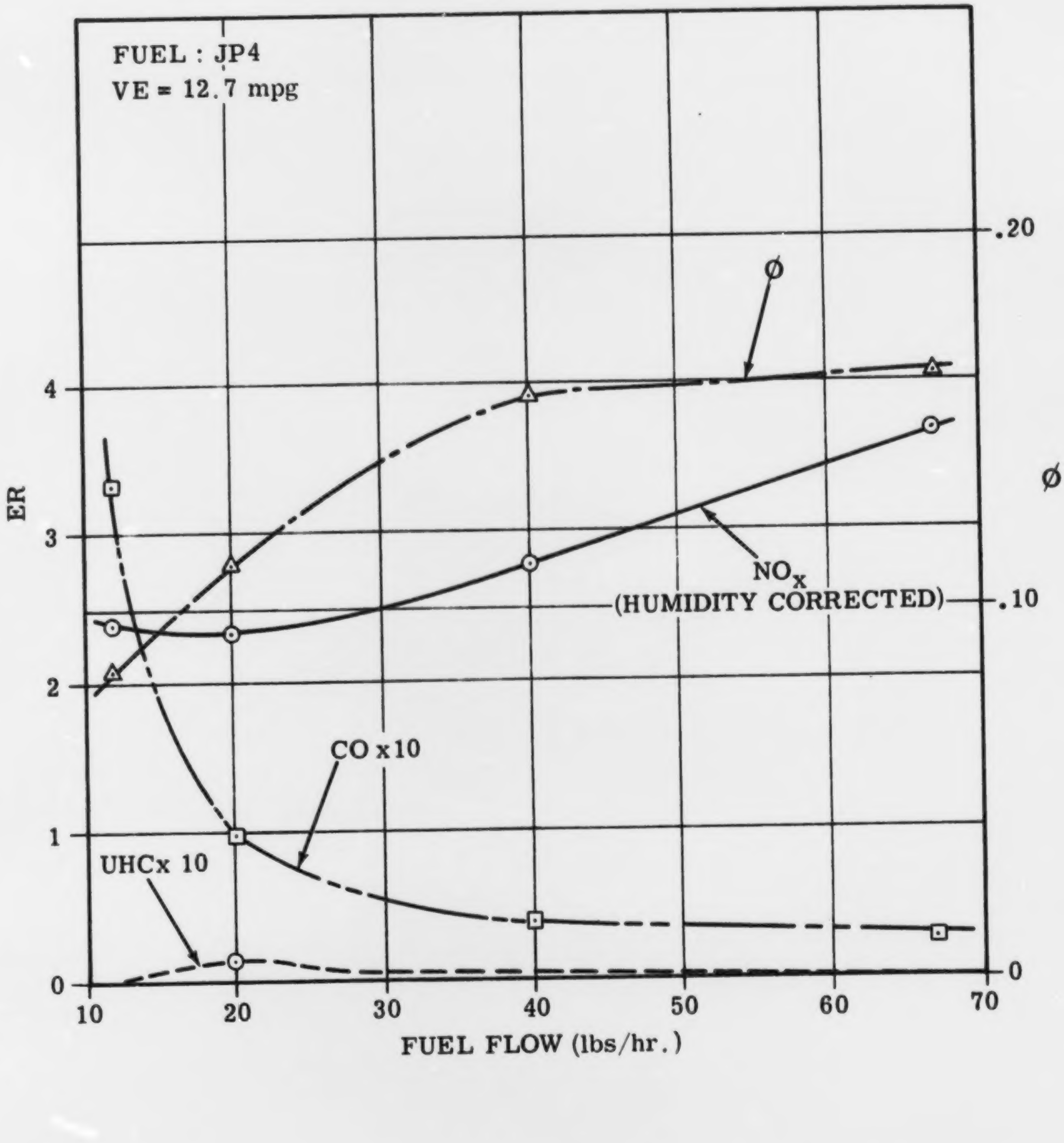

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FIGURE 4.45 CROSS SECTION OF COMBUSTOR ASSEMBLY FOR REGENERATOR BYPASS EVALUATION

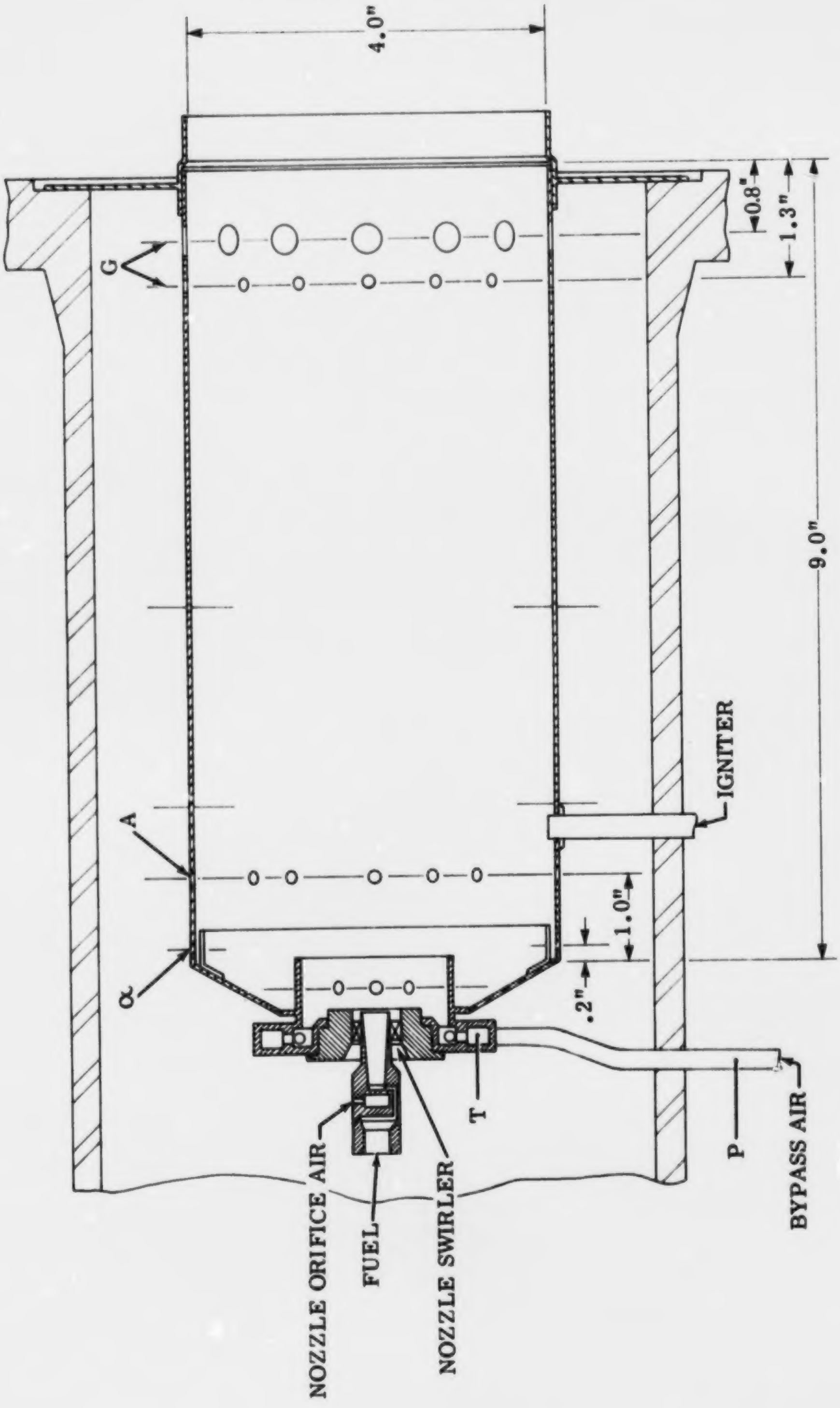
4.0"
0.8"
1.3"
G
9.0"
IGNITER
A
1.0"
.2"
α
T
P
BYPASS AIR
NOZZLE ORIFICE AIR
FUEL
NOZZLE SWIRLER

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FIGURE 4.46 EFFECT OF REGENERATOR BYPASS ON NO_x AND CO EMISSIONS

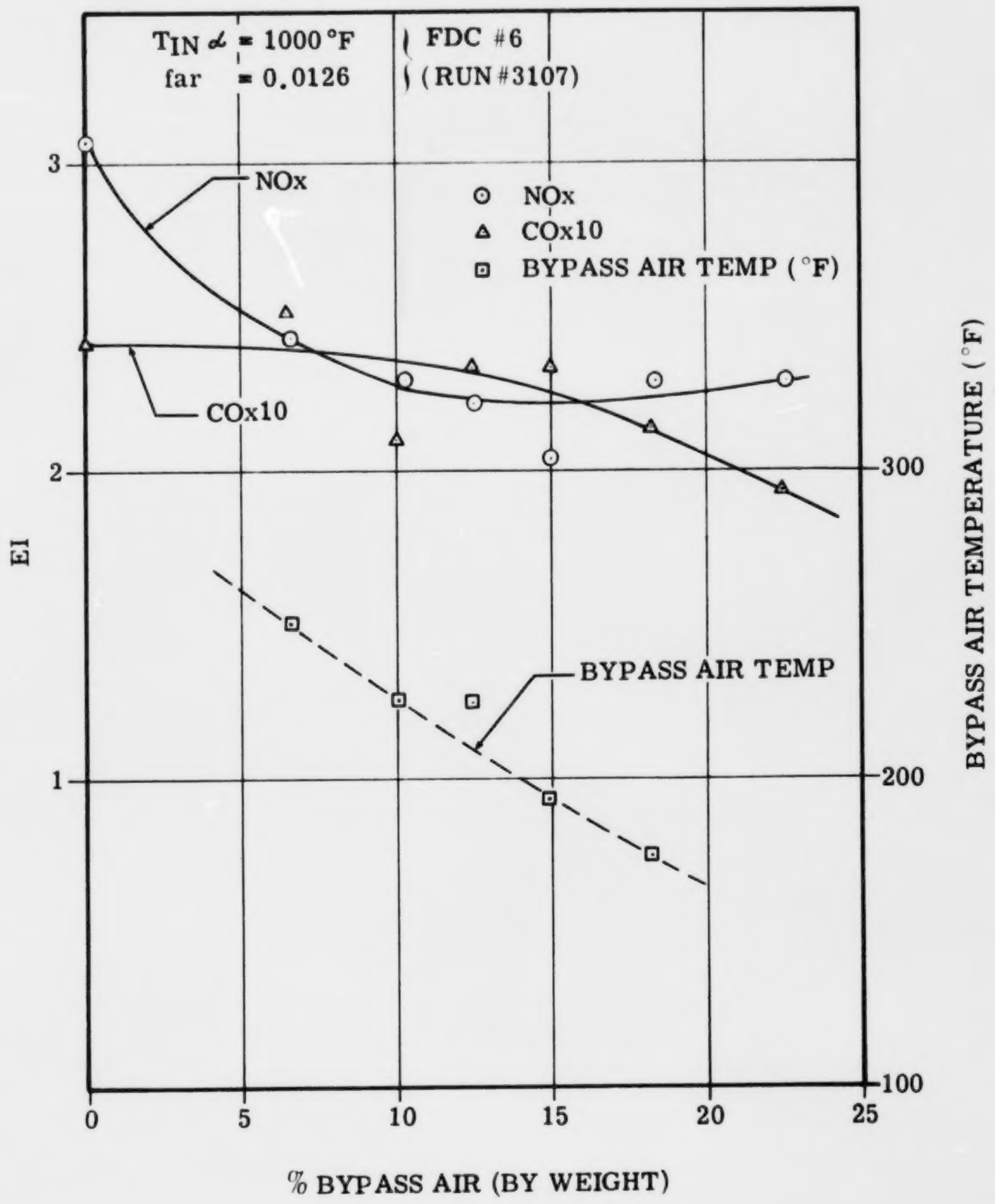

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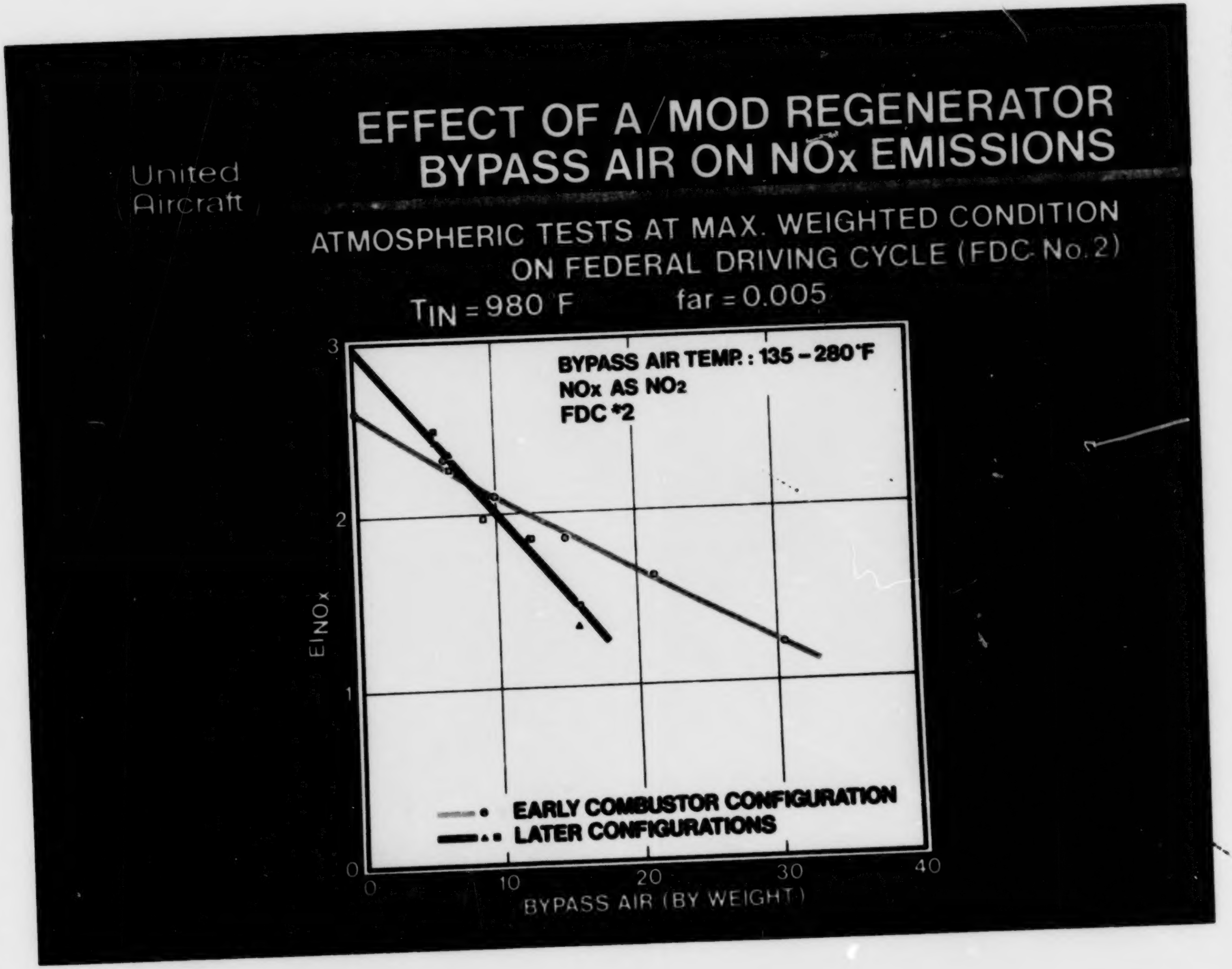
FIGURE 4.47 EFFECT OF REGENERATOR BYPASS ON NO_x EMISSIONS



United Aircraft

EFFECT OF A/MOD REGENERATOR BYPASS AIR ON NO_x EMISSIONS

ATMOSPHERIC TESTS AT MAX. WEIGHTED CONDITION ON FEDERAL DRIVING CYCLE (FDC No. 2)

$T_{IN} = 980$ F   far = 0.005

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5. DISCUSSION OF RESULTS

The development programs on the two combustors bring into focus several factors concerning approaches to be taken for emission controls. Some of the more important factors are discussed in this section.

5.1 Development Philosophy

Conceptually two approaches may be considered for developing a low emissions combustor:- (i) A system with a rich primary zone $(\phi_{PZ}>1)$ to reduce reaction zone temperatures and consequently NO_X formation, and an intermediate zone lean enough to keep NO_X formation rates low. The temperatures in the intermediate zone would be high enough to burn CO and hydrocarbons produced in the primary zone. This system would require a transition zone where mixing is rapid and dwell time at or near stoichiometry is minimal. An advantage is the good lean blow off limit which results from a rich primary zone. (ii) A system with a lean primary zone $(\phi_{PZ} < <1)$, with reaction zone temperatures low enough to reduce NO_X formation rates, and an intermediate zone with temperatures high enough to burn up the CO and hydrocarbons, but low enough to prevent NO_X formation.

The limitation on leaning the primary zone is its possible detrimental effect on the lean blow out limit. In both cases, rapid mixing and good homogeneity in the reaction zone are essential if low emissions are to be achieved. In the present program, the second approach has been used with varying results on the two classes of combustors. On Class A/Mod Combustor this approach has produced significant reductions, but best emission results are still well above targets. Further reductions can be achieved by extension of this approach, but meeting the EPA targets may be difficult.

5.2 Combustion Chemistry at Low Equivalence Ratios

A summary of important combustion reactions involving hydrocarbon fuel and oxidant in a lean reaction zone is shown in Table 5-1. The first three reactions involving chain branching of fuel and oxygen occur in the primary zone resulting in formation of CO. The conversion of CO occurs in the post primary zones (Reaction #4) along with recombination reactions (#5). The NO_X formations will mainly be in the primary zone if temperatures in the intermediate zone are maintained low enough. Class UB combustor studies have shown that a good upper limit temperature for the intermediate zone is 2750°R.

5.3 Class UB Combustor Results

5.3.1 Influence of Fuel Injection Process

An important portion of Class UB development involved investigations of a Simplex pressure atomizer, an air-assist atomizer, and an air-blast atomizer (Figure 4.3). The Simplex atomizer employs fuel pressure across a fine orifice to atomize the fuel. The fuel spray characteristics, viz. droplet size and spray angle are influenced by combustor operating pressure. The penetration of the spray and the cone angle are reduced at higher combustor pressures. These can create fuel rich regions in the core of the spray. Some improvement results from increasing air flow into the primary zone of the combustor.

The air-assist atomizer was constructed by admitting a small fraction of Combustor (ΔP) air in the (modified) secondary passage of a Duplex fuel nozzle. The Flow Number of the nozzle is approximately 1.0. A marked improvement in CO and NO_x emissions are observed (Figure 4.18) which is due to better atomization and leaning of the core of the jet. However, the increased spray angle has possibly resulted in greater wall quenching and hence the increased emission of UHC.

The basic problem with both the pressure and air-assist nozzle is their susceptibility to malfunction. It was observed that even a small streak in the fuel spray can result in relatively large changes in emission levels.

The air-blast atomizer employs the energy of high velocity air to provide the atomizing action. A venturi driven by the pressure loss across the combustor can provide the required velocities. Tests have shown that a 3% combustor pressure drop providing injection velocities between 240-370 feet/sec, can produce fuel drops of comparable size to those obtained by pressure atomizers (12). The fuel distribution is dictated mainly by the air flow pattern, and the atomization process ensures good mixing of fuel and air prior to combustion. The main drawback is the narrow stability limits. On the Class UB combustor program, the stability was improved by incorporating additional swirlers in the head end.

However, it is important to use an air-blast nozzle designed to cover the entire range of combustor fuel flows. The air-blast nozzle used in the UB program, being an off-the-shelf item, had a range of 10-50 lbs/hr. At fuel flows below 10 lbs/hr, the film formed by the fuel jets at the throat of the venturi may become non-continuous, resulting in poor atomization of the fuel and improper distribution. This shows up as a streaky, spiral tongue of orange flame at the core of the fuel nozzle. At operating conditions represented by FDC #1 (W_f = 8 lbs/hr), such a flame was observed and hence the high hydrocarbon and CO emissions. Although this point represents only 3% on the simulated Federal Driving Cycle, the disproportionately large values of UHC and CO result in integrated levels, significantly higher than the integrated levels over 96% of simulated Federal Driving Cycle (FDC #2, and FDC #3). In the case of the UHC emission the result is an $EI(CH_2)_n$ about 20% above target over the cycle, while over 96% of F.D.C. it is 85.5% below target. It is believed that an air-blast nozzle operating in the range of 5 to 70 lbs/hr would result in better overall emissions. Good light up performance might be ensured by incorporating a pilot nozzle in the core of the air-blast nozzle. At low-fuel flows (e.g., below 7 lbs/hr), all the fuel would be supplied from the pilot nozzle, and a well atomized spray thus obtained can give efficient combustion at start up. By incorporating a piloted air-blast nozzle, the performance requirements and good atomization over a wide burning range, may well be realized.

5.3.2 Intermediate Zone Temperature

The air-blast nozzle data (Figure 4.20) may be re-plotted for the two individual conditions (FDC #2 and FDC #3) of the simulated Federal Driving Cycle. Figure 5.1 shows a curve, plotted against the computed primary zone equivalence ratio. On FDC #2, which is the maximum weighted condition (76%), ϕ_{PZ} varies from 0.438 to 0.463 and on FDC #3, which represents 20% of Federal Driving Cycle, ϕ_{PZ} varies from 0.631 to 0.671. The wide disparity in these ranges reflects the variation and magnitude of individual emissions. The high CO and UHC emissions correspond to the low end of FDC #2 range while the high NO_X corresponds to the high end of FDC #3 range. The slopes of the individual curves generally reflect the effect of reaction zone temperatures. Higher temperatures resulting from higher primary zone equivalence ratios increase NO_X and reduce CO and UHC emissions. The CO and UHC with increasing ϕ_{PZ} observed on the FDC #3 range of equivalence ratios may be attributed to the presence of lean pockets in the mixtures at the high end. Figure 5.2 shows variations of CO and NO_X emissions with computed primary zone equilibrium temperature for FDC #2. Also shown are the targets (on FDC) emissions. In the vicinity of target, the CO emissions appear highly dependent on the temperature. The primary zone equilibrium temperature may be considered as intermediate zone temperature since no additional air is admitted in this zone. The required temperature for target, or better, CO emissions must be above 2740°R, and for target, or better, NO_X emissions the temperature must be below 2762°R. An average temperature (as calculated here) of 2750°R should better targets for both the species.

5.4 Class A/Mod Combustor Results

The development of Class A/Mod combustor followed a pattern similar to that of the simple cycle combustor; however, the high inlet temperatures characteristic of this cycle, made it more difficult to achieve large reductions in NO_X levels while maintaining CO emissions at or below specific levels.

The incorporation of staged swirl in the head end allowed flame stability to be maintained even as the equivalence ratio in the primary zone was being reduced progressively. In the final configuration of the combustor (Figure 4.40), approximately 44% of the total air flow is introduced through the head end and single row of primary zone holes. Thus, the Class A/Mod combustor was designed to have a short lean primary zone to minimize NO_X formation, and a relatively long intermediate zone to permit CO and UHC oxidation. Visual observations and photographs of the combustion process indicated that the combustor operated with a stable flame having a uniform appearance (Figure 5.3).

The photograph of the flame at the maximum weighted condition on the simulated Federal Driving Cycle (T_{in} = 980°F, far = 0.0050), shows a bluish flame outside of the flame holder and an almost colorless flame inside. The indication is over-lean conditions exist inside of the flame holder, rendering a pre-quench of part of the reacting mixture. It is believed that a better distribution of air flows in the head end may result in lower CO emissions while maintaining the NO_x emissions at the levels shown, Table 4-15.

The air blast nozzle used with the Class A/Mod Combustor had an operating range of 10-40 lbs/hr. This was identical to the nozzle used with the Class UB Combustor. On the simulated Federal Driving Cycle (Table 4-13), three points (FDC #'s 1, 2 and 3) represent fuel flow rates at or below the lower limit of operating range. These together represent 59% of the time on the simulated Federal Driving Cycle. At fuel flows below the lower limit of the operating range, the film formed by the fuel jets at the throat of the venturi could become non-continuous, resulting in poor atomization of the fuel and improper distribution. Also the pressure loss on FDC #2, which represents 34% of FDC, is 0.988 psi compared with 1.8 psi on the maximum weighted condition for Class UB. The lower energy of atomizing air with Class A/Mod may be responsible for the relatively higher CO emissions. Hence an optimized air-blast nozzle should result in better atomization and emissions at the lower fuel flow points on the simulated Federal Driving Cycle.

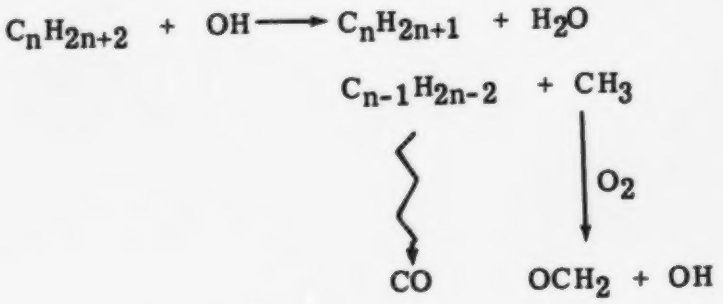
A comparison of mass emissions of fixed geometry combustors for regenerative and simple cycle engines is shown in Figure 5.4. The integrated cycle emissions shown are from (1) Chrysler regenerative combustor (13), (2) simulated GM regenerative combustor (14), (3) United Aircraft Class A/Mod regenerative combustor, and (4) United Aircraft Class UB simple-cycle combustor. While the Chrysler emissions appear to be based on a simulated cycle similar to that of the Class A/Mod combustor, the GM emissions are based on a HEW cycle not specified (in Reference 14). From this comparison the significantly better emissions achieved under the present program is apparent. It should be noted that Chrysler's data was from full engine operation with simulation of the severe transients during actual driving which are characteristic of regenerative gas turbine engines due to their load shedding proplems. Chrysler has indicated that steady state engine and rig measured NO_x emissions may be less than over the road emissions by about 50%.

TABLE 5.1 COMBUSTION SCHEME FOR HYDROCARBONS WITH EXCESS OXYGEN

1 **Chain Branching and Attack on O_2**

$$H + O_2 \longrightarrow OH + O$$

2 **Attack on Fuel**



$$C_nH_{2n+2} + OH \longrightarrow C_nH_{2n+1} + H_2O$$

$$\begin{tikzcd} C_{n-1}H_{2n-2} \arrow[d, squiggly] & + CH_3 \arrow[d, "O_2"] \\ CO & OCH_2 + OH \end{tikzcd}$$

3 **Other Chain Branching Reactions**

$$OH + H_2 \longrightarrow OH + H$$

$$OH + H_2 \longrightarrow H_2O + H$$

$$OCH_2 + O \longrightarrow HCO + OH$$

$$O + H_2O \longrightarrow OH + OH$$

4 **Conversion of CO:** $CO + OH \longrightarrow CO_2 + H$

5 **Recombination:** $O + O + M \longrightarrow O_2 + M$

$$H + OH + M \longrightarrow H_2O + M$$

$$H + H + M \longrightarrow H_2 + M$$

FIGURE 5.1 VARIATION OF CLASS UB COMBUSTOR EMISSIONS WITH PRIMARY ZONE EQUIVALENCE RATIO - AIR-BLAST ATOMIZER (HUMIDITY CORRECTED)

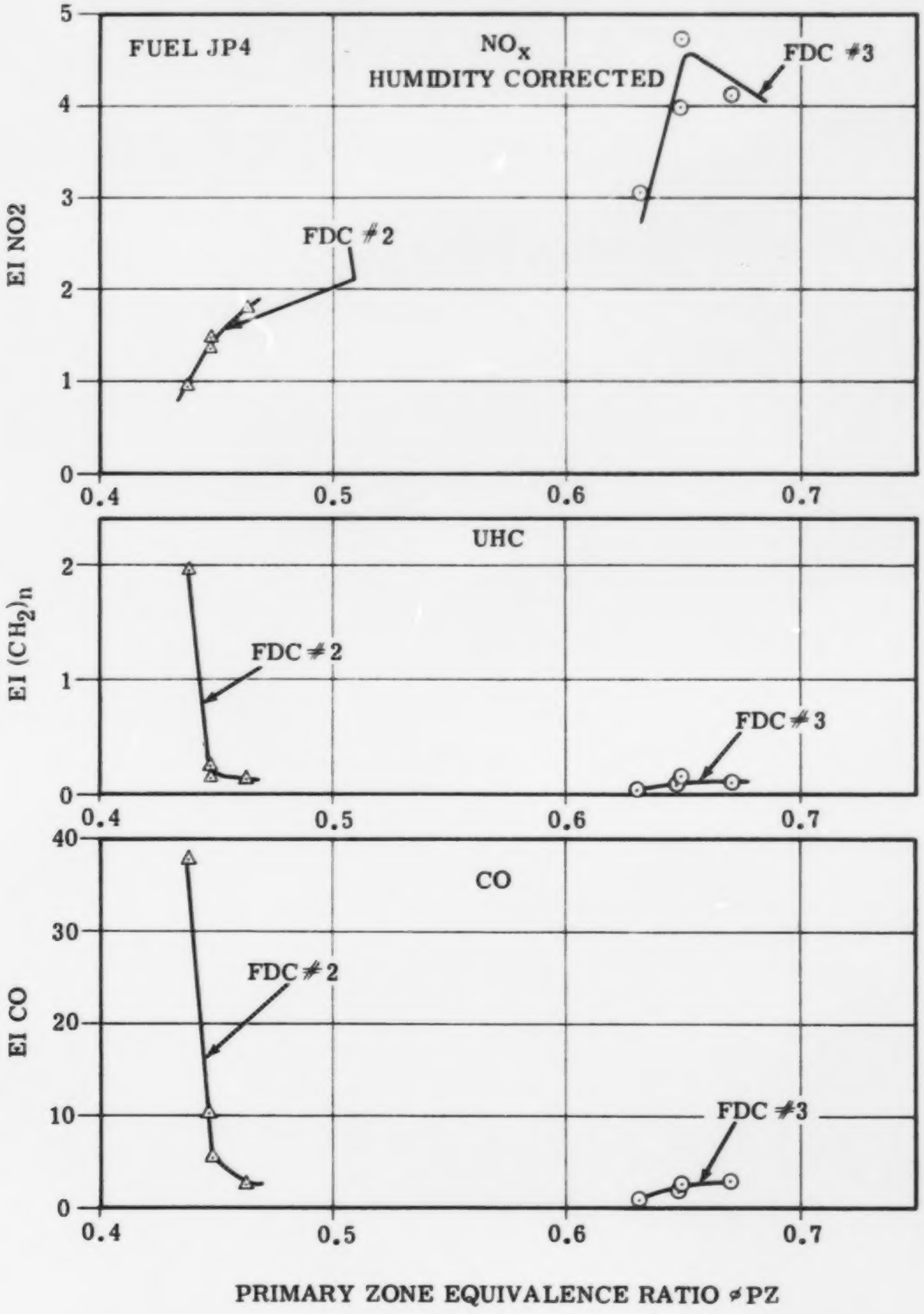


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FIGURE 5.2 VARIATION OF CLASS UB COMBUSTOR EMISSIONS WITH PRIMARY ZONE EQUILIBRIUM TEMPERATURE (HUMIDITY CORRECTED)

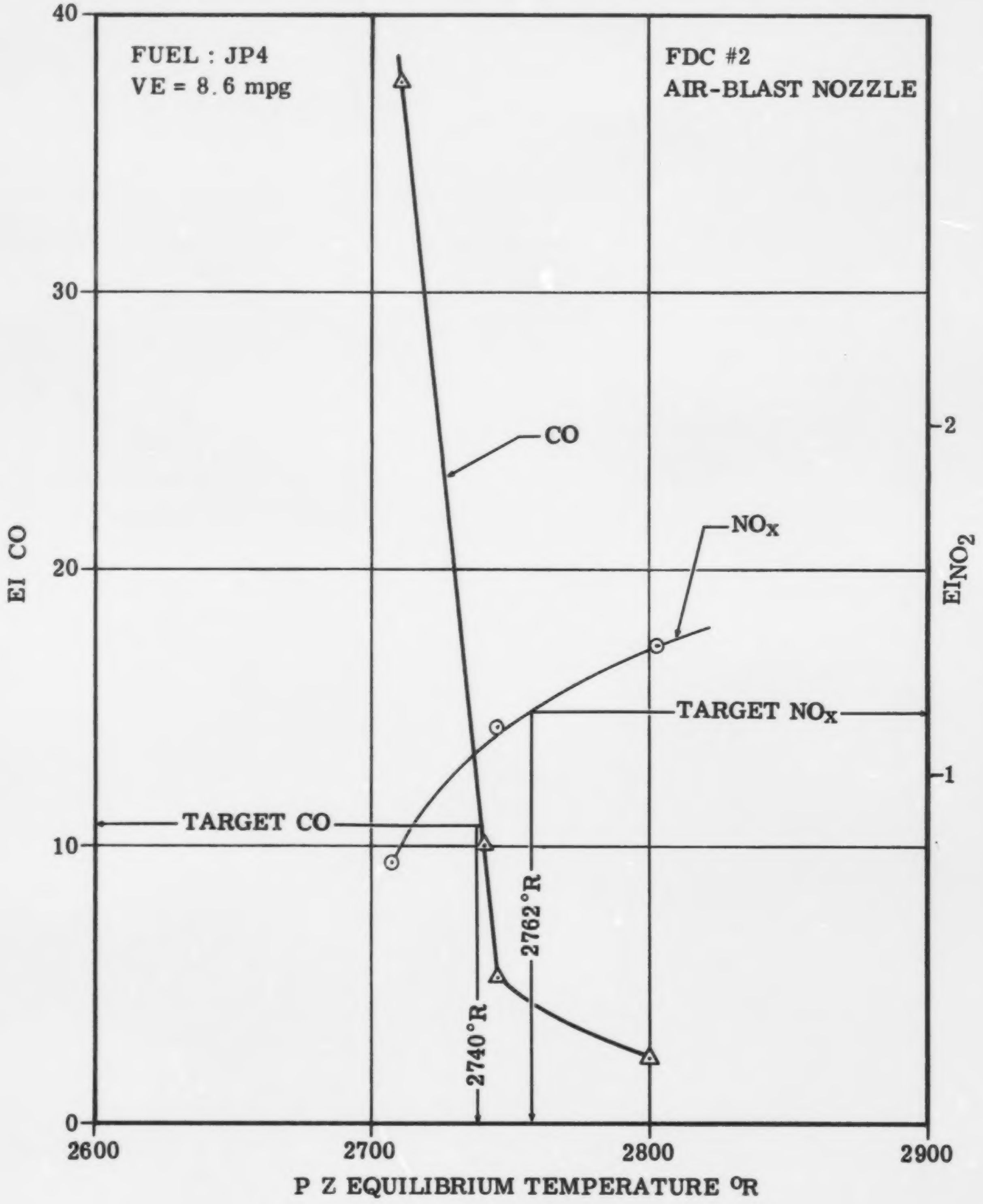

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FIGURE 5.3 FLAME PHOTOGRAPHS FROM CLASS A/MOD COMBUSTOR

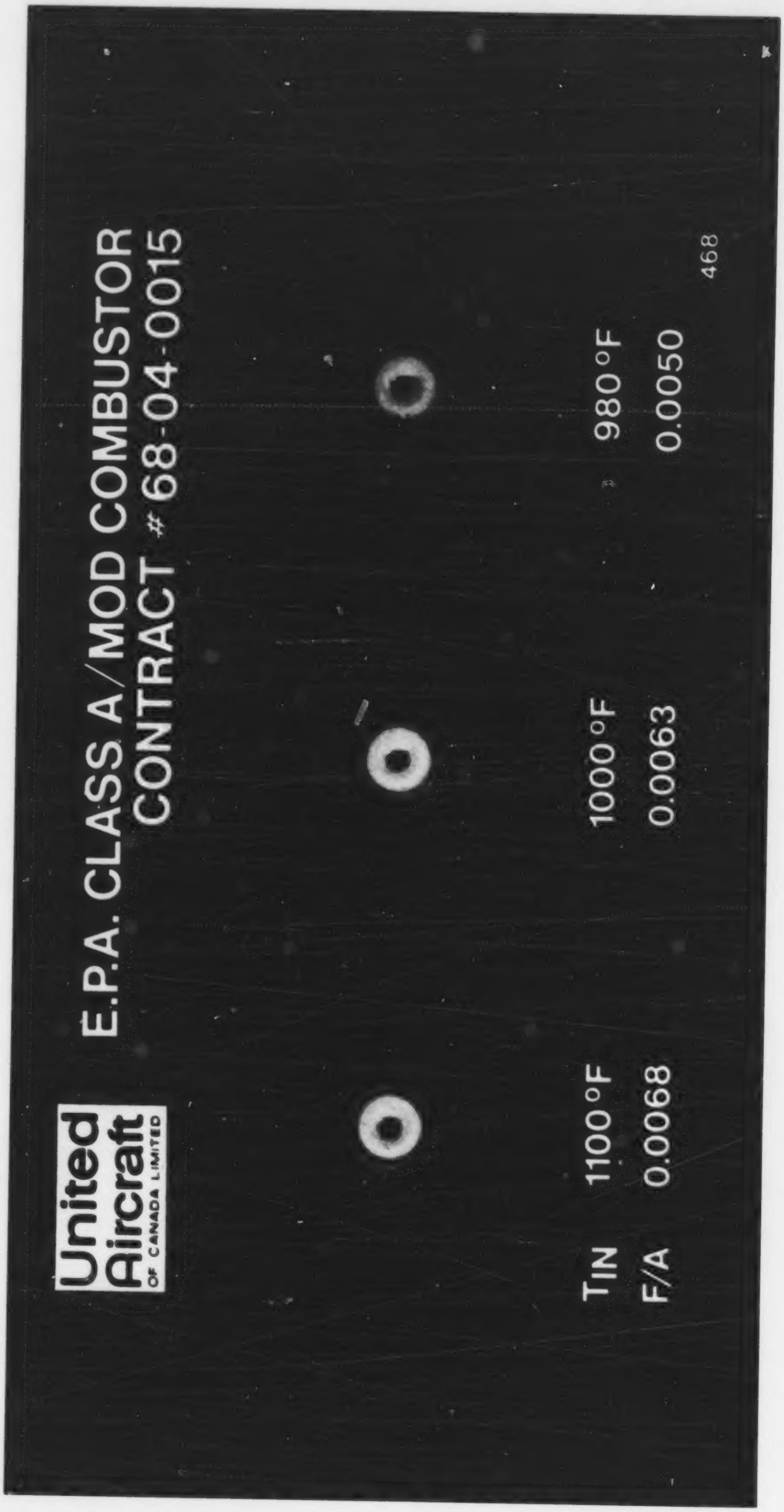
E.P.A. CLASS A/MOD COMBUSTOR
CONTRACT # 68-04-0015
United Aircraft of Canada Limited
T_{IN}
F/A
1100 °F
0.0068
1000 °F
0.0063
980 °F
0.0050
468

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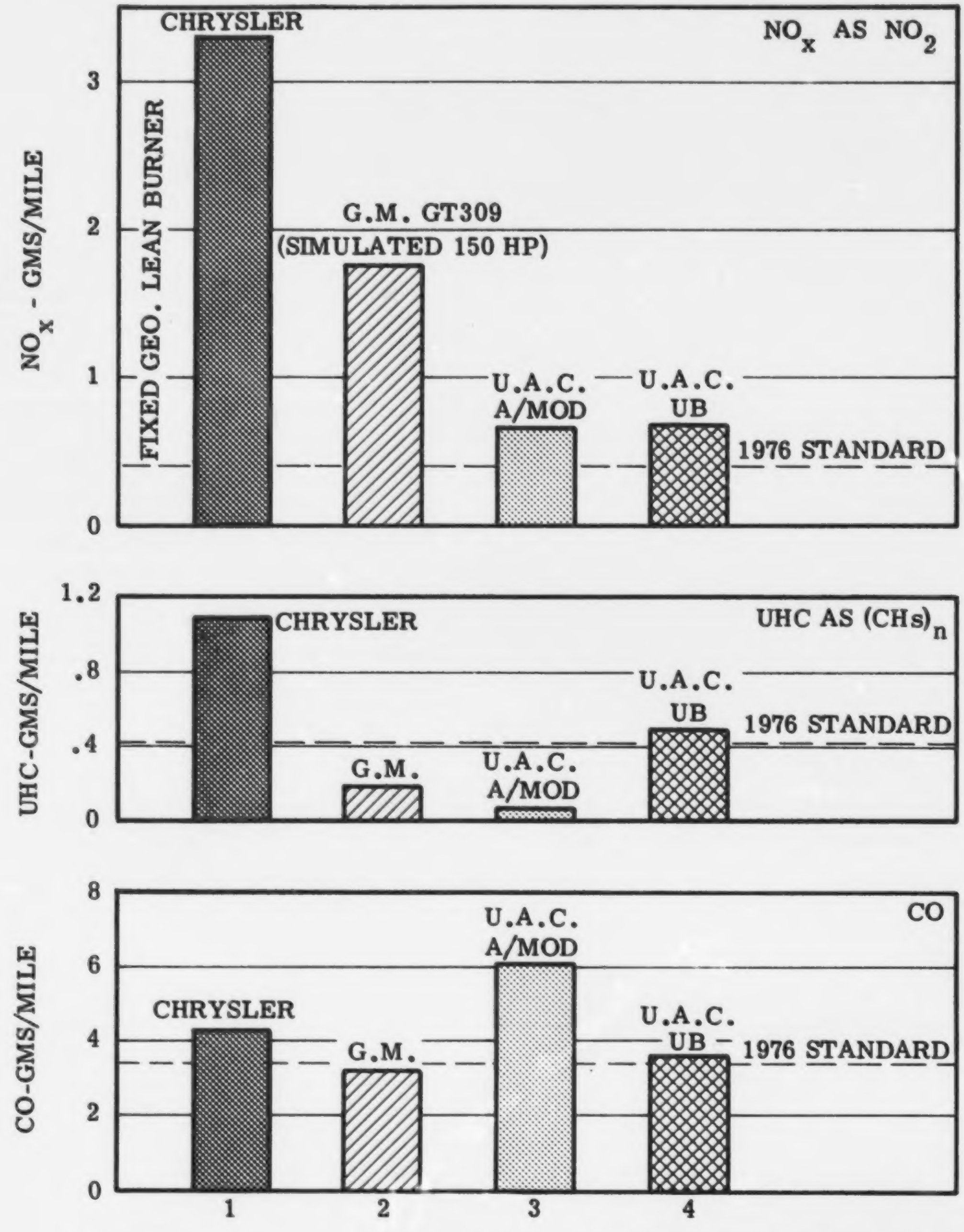
FIGURE 5.4 COMPARISON OF MASS EMISSIONS OF REGENERATIVE AND SIMPLE CYCLE COMBUSTORS (HUMIDITY CORRECTED EXCEPT G.M. DATA)



1. CHRYSLER - ENGINE TEST RESULTS WITH FULL TRANSIENT SIMULATION(13)

2. G.M. - GT 309 RIG RESULTS SCALED TO 150 HP(14)

3. } U.A.C. - RIG RESULTS - SIMULATED FDC, 12.7 mpg FOR CLASS A/MOD AND 8.6 mpg FOR CLASS UB
4. }

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6. CONCLUSIONS AND RECOMMENDATIONS

The investigations described in the report have significantly covered both the analytical and developmental aspects of gas turbine combustor emissions. It is believed this work has resulted in a better understanding of some of the underlying factors contributing to emissions from continuous combustion systems.

The program has shown that careful modifications to the head end aerodynamics, combined with use of dependable fuel atomizers, can result in overall reduction of all three principal pollutants. Substantial reductions in emission levels have been accomplished by employing conventional simple geometry can combustors for both the simple cycle and regenerative cycle applications. It is seen that low NO_x levels can be achieved in both cases, and that CO levels can be kept to a minimum by ensuring good mixing in the reaction zone, and maintaining sufficiently high intermediate zone temperatures. The unburned hydrocarbon (UHC) emissions can be controlled by reducing the quenching effects of film cooling air, and by the use of a suitable fuel atomizer.

The research program has utilized most of the tools available to a combustion engineer - i.e., analytical models, water model studies, atmospheric and full pressure rig studies. From the viewpoint of exhaust emissions some of these tools have limitations which are not seen in normal combustion work. In spite of these limitations, it is believed that all these techniques, and others more refined, can be put to good use in any low emission work.

6.1 Conclusions - General

a) Conventional can type combustors operating with lean and well mixed primary zones and carefully controlled quenching rates can achieve low overall levels of pollutant formation.

b) The combustor hardware can be kept simple and practical. Initial designs of the flame tubes can conform to standard practice but for a few differences - principally reaction zone equivalence ratio, controlled intermediate zone and wall temperatures, and mixing techniques in the reaction zone.

c) In general, emissions of CO and UHC are caused by low reaction temperatures, poor atomization and quenching effects of wall cooling air. Increasing the primary zone temperature to reduce CO and UHC in exhaust emissions tends to cause large increases in NO_x production, which is principally dependent on temperature. It is believed that a lean and cool head-end combustor can yield low NO_x emissions while CO and UHC emissions can be controlled by maintaining the intermediate zone temperature high enough to burn CO ($>2750°R$) but low enough not to produce significant NO_x ($<2900°R$).

d) Good fuel atomization and homogeneity of reacting mixtures are essential to reduce rich pockets which would promote NO_x formation. Staged swirl is an effective means of promoting homogeneity and stability in a lean primary zone.

e) Good flame stability and wide turndown ratio can be maintained in spite of a very lean primary zone due to detailed geometry and piloting effects. The re-circulatory gas flow paths, established by staged swirl in the head end, improve significantly the lean blow-out performance of the combustors.

f) The air-assist and air-blast atomizers have significant advantages over pressure atomizing nozzles in terms of reducing emissions of CO, UHC and to a lesser extent NO_x. The air-blast atomizer appears to have much greater potential for reliability as well as lower system cost. A piloted air-blast would be a good approach to obtain a wider operating range for the fuel nozzle.

g) The intermediate zone if maintained at sufficiently high temperatures can be used to consume CO and UHC. The investigations on Class UB combustor have shown that an optimum temperature for CO and UHC consumption in the intermediate zone is 2750°R. Increasing the residence time in the intermediate zone can also result in more oxidation of CO and UHC.

h) The variation of NO_x emissions with overall fuel-air ratio appears to be significantly influenced by the primary zone mixing conditions. For example, with a combustor having a lean primary zone with early quench, the NO_x emission indices have been observed to decrease with increase in overall fuel-air ratio whereas with conventional combustors ($\phi_{PZ} \simeq 0.9$) the trend is reversed. These effects suggest the strong influence of primary zone aerodynamics on emissions.

i) The humidity of the inlet air is of importance in the evaluation of NO_x emission levels from gas turbine combustors. The magnitude of the effect also appears to depend on the leanness of the primary zone and loading of the combustor. The effect has varied from 10% to 25% for a standard humidity of 1.07% by weight depending on the combustor design and the operating conditions.

6.2 Conclusions - Developmental

a) Water modeling is a useful technique in establishing flow paths and distributions. Measurements of residence time from water model studies are only indications of trends.

b) Analytical modeling can be a useful tool for predicting NO_x production rates from candidate combustor design configurations and subsequent modifications. It is also useful for predictions of effects of inlet moisture, temperature and pressure on NO_x emissions.

c) Initial development of the combustor can be quickly accomplished with low pressure (atmospheric) testing, and substantial reductions in NO_x levels can be achieved. This has proven to be a cost-effective tool. However, the apparently strong detrimental effect of low pressures on lean blow-out, limits the extent to which the head end of the combustor can be developed for low NO_x emissions.

d) Interpretation of emission data from atmospheric tests rely on good estimates of effect of full pressure on emissions. While kinetic model predictions were made for NO_x, the effect of pressure on CO and UHC could only be guessed in the absence of a suitable model. From this viewpoint, the emission levels from atmospheric tests could only be interpreted on a qualitative basis.

e) Increasing the combustor inlet pressure results in increased NO_x emissions and reduced CO, UHC emissions. Pressure also affects the fuel spray characteristics - spray angle and droplet size - and lean limit. Major development for reducing emissions must therefore be done at representative conditions.

f) Full axis viewing of the flame, through an observation window, provides invaluable qualitative understanding of flame characteristics as related to combustor emissions. Also, a majority of unintended combustion changes due to fuel or air inlet asymmetries can be spotted as flame asymmetries, streaks or spottiness. Flame locations, color, brightness and stability render a qualitative understanding of flame properties as they relate to emissions.

6.3 Conclusions - Class UB Combustor for the Simple-Cycle Engine

Development has produced:

- Simple small combustor
- Good turndown ratio
- Low pressure drop
- Excellent temperature distribution
- Excellent stability
- Low emissions - NO_x 29% above target, CO 7% above target, UHC 20% above target

Indications are that there is no need for variable geometry and that this combustor can be further developed quite easily to meet and probably better standards over a simulated Federal Driving Cycle.

6.4 Conclusions - Class A/Mod Combustor for the Regenerative Cycle Engine

Employment of Class UB techniques has resulted in:

- Simple small combustor
- Excellent stability
- Good turndown ratio
- Excellent temperature distribution
- Substantially reduced emission values - NO_x to 46% above target,
  CO to 80% above target,
  and UHC negligible

The emission levels achieved over a simulated Federal Driving Cycle are significantly better than the best reported data for fixed geometry combustors (Figure 5.4). It is believed that, with further development along the same lines, emission levels much closer to targets can be achieved. In this case, a simple form of variable geometry controlling air flow into the head end may also be considered to achieve target emissions. The combustor has also shown good symmetry, Figure 5.3.

6.5 Recommendations

It is recommended that the work undertaken in this program be continued on both classes of combustors. The belief is that for a fraction of the present effort, either or both combustors can be developed to meet or better the Federal emission standards. On Class UB, this would result in a small fixed geometry combustor, while on Class A/Mod, any variable geometry incorporated would be of a simple form involving control of air flow into the head end swirlers. In both cases, fuel injection would be through a single air-blast nozzle with no variability involved.

Several other aspects examined under the present program merit further investigation. These are (i) Effect of ambient humidity on primary zone kinetics, (ii) Development of a reliable CO model and refinement of NO_x models to account for local mixture conditions, and (iii) Investigation of fuel injection systems oriented towards low emissions. Piloted air-blast nozzles might warrant particular attention.

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APPENDIX A

WATER MODEL TESTING
OF SIMPLE CYCLE FLAMETUBE

A.1.0 INTRODUCTION
A.2.0 Results of Flow Path Development
A.3.0 Results of Flow Split Assessment
A.4.0 Results of Recirculation Rate Assessment
A.5.0 Results of Particles Speed Assessment
A.6.0 Prediction of Flow Speeds & Residence Times

Figure A.1 Distribution of Recirculation in Primary Zone
Figure A.2 Distribution of Recirculation in Dilution Zone
Figure A.3 Distribution of Flow Speeds in Water Model Class 'UB' Final Configuration
Figure A.4 Distribution of Flow Speeds in Water Model Class 'UB' Final Configuration

Table A.1 Speed Measurement Zones
Table A.2 Trace Lengths
Table A.3 Combustor Geometry
Table A.4 Flow Splits
Table A.5 Residence Times

A.1.0 INTRODUCTION

A.1.1 The Class UB water model with alternative head to Figure 4.1 was set up in a vertical position in the water analogy rig, Figure 3.3.

A.1.2 A light source was arranged on each side of the working section, consisting of photographic lamps of 1000 watt and 650 watt power beamed through a series of simple slots to give a plane of light .060" to .130" deep.

A.1.3 Photography was performed with a Graflex camera using polaroid film (3000 ASA).

A.1.4 Flow pattern tracers consisted of aluminum dust for general flow path recording, and polystyrene balls for more detailed work.

A.1.5 Flow splits and recirculation were established by using a very few polystyrene tracers and observing the path of individual balls (i.e. noting whether the ball was recirculated or passed directly downstream, and counting the number of rotations in the recirculation zones).

A.1.6 An attempt was made to measure the speed of tracers by photographing at various shutter speeds, using a large number of tracers.

A.1.7 All tests were run at ΔP of approximately 4" H_2O except when tracing the path of a single tracer when the ΔP was reduced. Higher ΔP's were unattainable due to rig limitations.

A.1.8 10 configurations were tested as detailed in the following section.

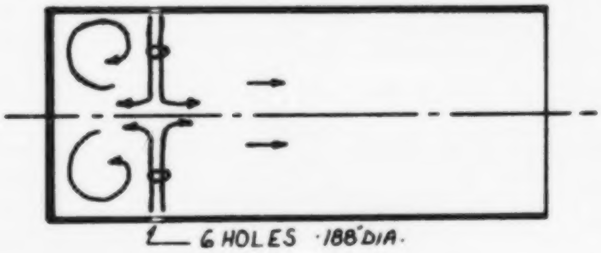
A.2.0 RESULTS OF FLOW PATH DEVELOPMENT

See diagrams.

A.2.0 RESULTS OF FLOW PATH DEVELOPMENT

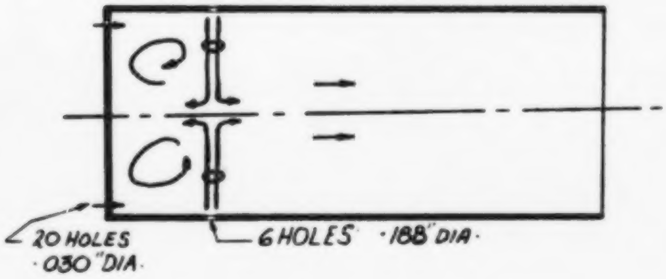
CONFIGURATION COMMENTS

A.2.1


6 HOLES .188"DIA.

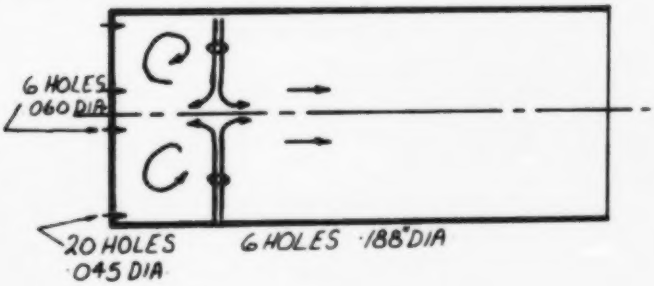
Strong penetration from 6 holes .188" dia.
Strong recirculation.

A.2.2


20 HOLES
.030"DIA.
6 HOLES .188"DIA.

As above.
Flow from 20 holes .030" dia. weak.

A.2.3

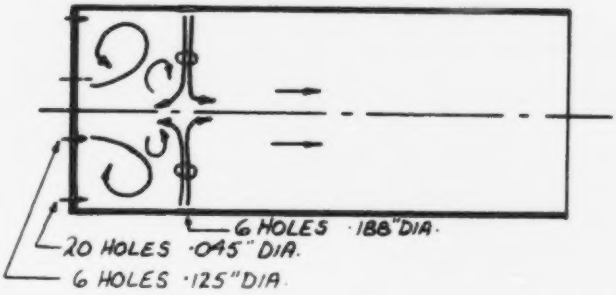

6 HOLES
.060 DIA
20 HOLES
.045 DIA
6 HOLES .188"DIA

Penetration of 6 holes .188" dia. still strong.
Recirculation zone weaker.
Better penetration from 20 holes .045" dia.
Flow from 6 holes .060" dia. weak.

A.2.0 RESULTS OF FLOW PATH DEVELOPMENT (continued)

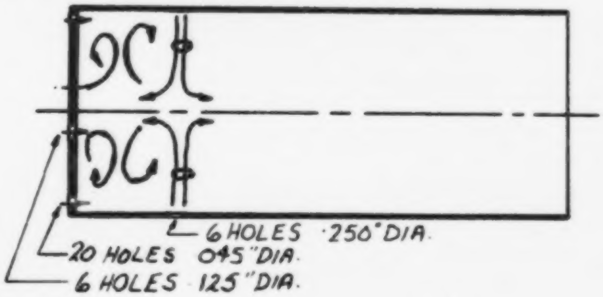
CONFIGURATION | COMMENTS

A.2.4


6 HOLES ·188"DIA
20 HOLES ·045"DIA
6 HOLES ·125"DIA

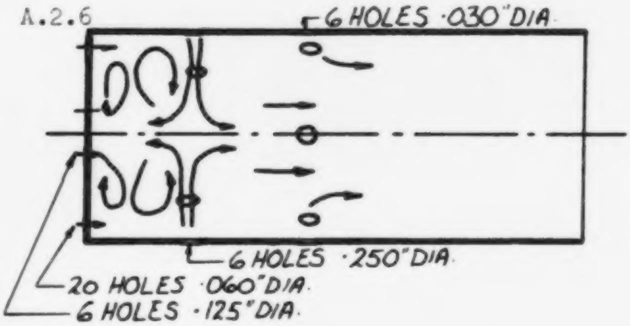
Penetration 6 holes .188" still strong.
6 holes .125" dia. very strong.
Recirculation reversed.
Small secondary recirculation upstream of primary jets.

A.2.5


6 HOLES ·250"DIA
20 HOLES ·045"DIA
6 HOLES ·125"DIA

6 holes .250" dia. flow strengthened.
Double vortex.

A.2.6

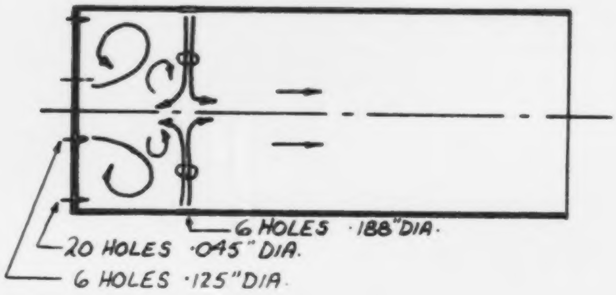

6 HOLES ·030"DIA
6 HOLES ·250"DIA
20 HOLES ·060"DIA
6 HOLES ·125"DIA

Double vortex persists.
6 holes .030" dia. weak, little penetration.

A.2.0 RESULTS OF FLOW PATH DEVELOPMENT (continued)

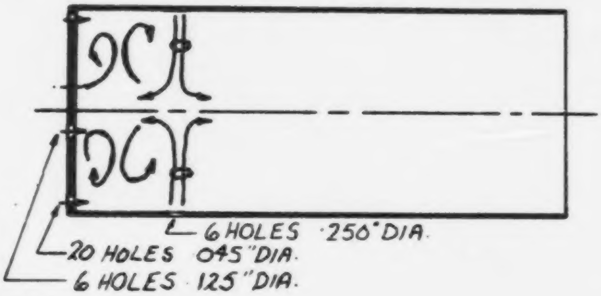
CONFIGURATION | COMMENTS

A.2.4


6 HOLES .188"DIA.
20 HOLES .045" DIA.
6 HOLES .125"DIA.

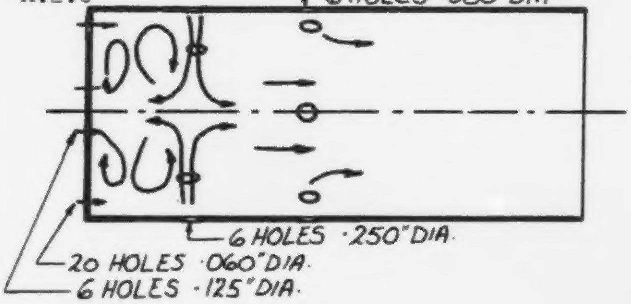
Penetration 6 holes .188" still strong.
6 holes .125" dia. very strong.
Recirculation reversed.
Small secondary recirculation upstream of primary jets.

A.2.5


6 HOLES .250"DIA.
20 HOLES .045"DIA.
6 HOLES .125"DIA.

6 holes .250" dia. flow strengthened.
Double vortex.

A.2.6


6 HOLES .030"DIA.
6 HOLES .250"DIA.
20 HOLES .060"DIA.
6 HOLES .125"DIA.

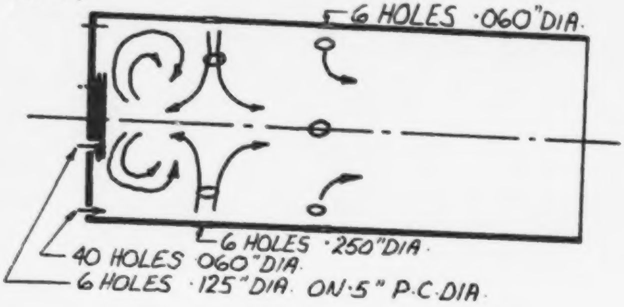
Double vortex persists.
6 holes .030" dia. weak, little penetration.

A.2.0 RESULTS OF FLOW PATH DEVELOPMENT (continued)

CONFIGURATION

COMMENTS

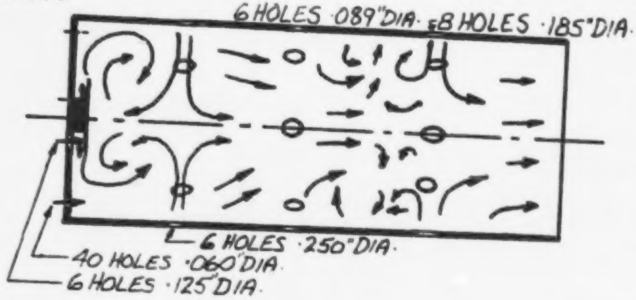
A.2.7


6 HOLES ·060"DIA·
6 HOLES ·250"DIA·
40 HOLES ·060"DIA·
6 HOLES ·125"DIA· ON·5" P·C·DIA·

Single vortex recirculation restored.

6 holes .060" dia. adequate penetration.

A.2.8

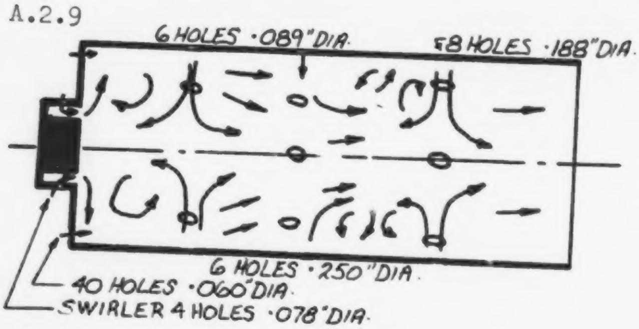

6 HOLES ·089"DIA·
8 HOLES ·185"DIA·
6 HOLES ·250"DIA·
40 HOLES ·060"DIA·
6 HOLES ·125"DIA·

As above.

Good penetration from dilution holes (8 holes .188" dia.).

Note vortex upstream of dilution holes.

A.2.9


6 HOLES ·089"DIA·
8 HOLES ·188"DIA·
6 HOLES ·250"DIA·
40 HOLES ·060"DIA·
SWIRLER 4 HOLES ·078"DIA·

As above.

A.2.10

As above, but swirler holes .109" dia.

No apparent change.

A.3.0 RESULTS OF FLOW SPLIT ASSESSMENT (Final Configuration only)

A.3.1 Primary Zone

The paths of 51 balls were observed entering the primary zone holes (6 holes .250" dia.).

21 were entrained in the recirculation zone, 30 passed downstream.

Hence, 41.2% of primary jet air is recirculated.

Of the balls passing through the dome holes (40 holes .060" dia.) and swirler, none appeared to escape the recirculation zone, though some difficulty was experienced with tracing these flows.

Hence, 100% of dome and swirler air may be considered to recirculate.

A.3.2 Dilution Zone

Of 19 balls observed passing into the first row of dilution holes (8 holes .188" dia.), 9 were recirculated in the vortex just upstream of the holes, 10 passed downstream.

Hence, 47.3% of 1st row dilution hole air is recirculated.

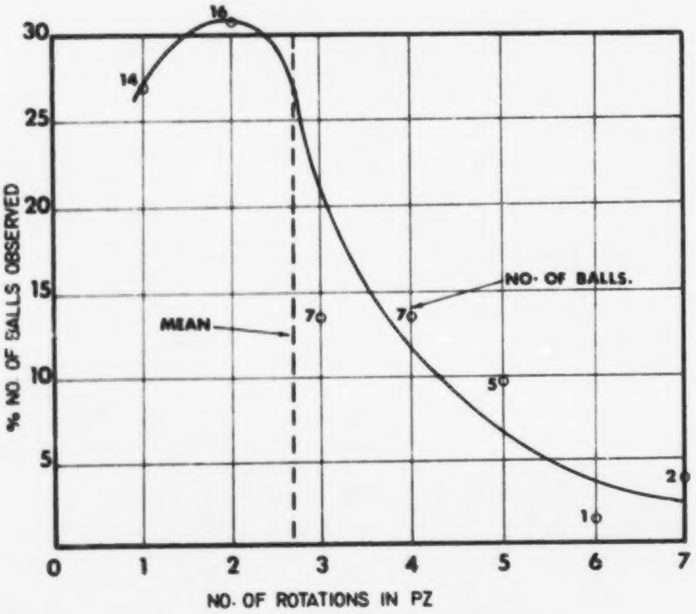
All of the 2nd row dilution hole air appeared to pass downstream.

A.4.0 RESULTS OF RECIRCULATION RATE ASSESSMENT

A.4.1 Primary Zone Vortex

52 balls were observed.

The arithmetic mean number of rotations was 2.7 times. Max. = 7 rotations, min. = 1 rotation. The distribution is shown in Figure A.1.



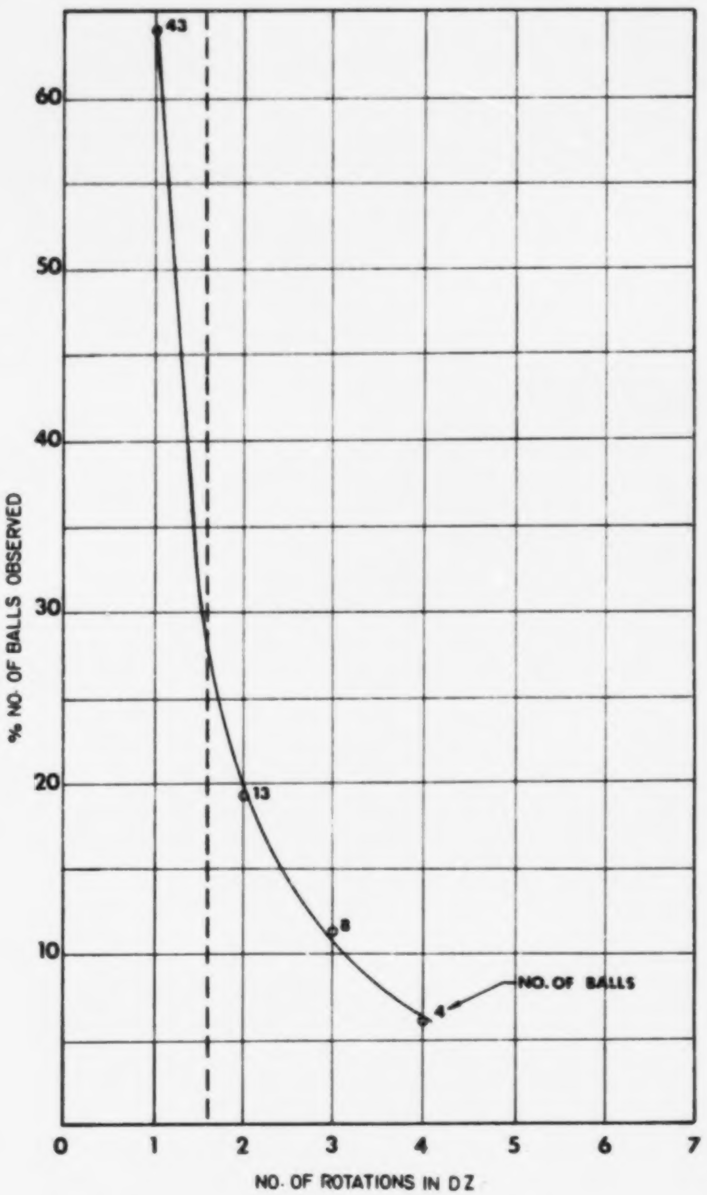


Figure A.2 - Distribution of Recirculation in Dilution Zone

A.4.2 Dilution Zone Vortex

68 balls were observed.

The arithmetic mean number of rotations was 1.58 times. Max. 4 rotations min. = 1 rotation.

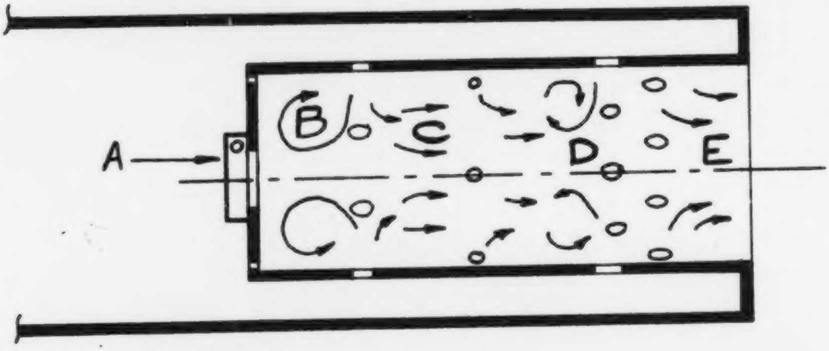
The distribution is shown in Figure A.2.

A.5.0 RESULTS OF PARTICLE SPEED ASSESSMENT

The flow inside the model flametube is multi-directional with components in the axial plane and two transverse planes. Also, the direction of any particle of fluid changes with time. Hence, speed should be assessed over the shortest possible interval of time.

This philosophy was adopted in the speed measurements and the photographs chosen for this exercise were those having the shortest exposure at which the trace lengths could be measured.

Due to the fact that some of the particles will have a considerable transverse component to the plane of photography, it is to be expected that the mean measured velocity will be lower than the true mean (this will not apply to Zone A, where the flow is generally axial except for relatively fine-scale turbulence).



A.5.0 RESULTS OF PARTICLE SPEED ASSESSMENT (continued)

Table A.1 - Speed Measurement Zones

Photograph No.	Shutter Speed	TRACE LENGTH				
		A	B	C	D	E
α	1/25 sec	.19 .13 .15 .17 .20 .11 .13 .15 .16 .10	.40 .10 .25 .11 .15 .50 .32 .11	.20 .28 .02 .03 .03 .10 .13	.17 .20 .10 .21 .25 .10	
β	1/25 sec		.11 .75 .45	.13 .10 .09 .02	.10 .15 .20 .10 .15 .20 .15 .12 .25	.25 .10 .25 .40 .35 .10
γ	1/2 sec	.5 .5 .5	Traces too long to measure			

Table A.2 - Trace Lengths

Photograph No.	Shutter Speed		TRACE LENGTHS			
		A	B	C	D	E
δ	1/2 sec		Traces too long to measure			
θ	1/25 sec		.25 .09 .10 .10 .08	.25 .08 .18 .12	.5 .15 .5 .35 .2 .11 .10 .40	.2 .3 .25 .10
Mean	1/25 sec	.124	.242	.1172	.224	.23

Hence, relative values for mean particle speeds in the water model are:

Zone A - 3.1 in/sec.
Zone B - 6.05 in/sec.
Zone C - 2.94 in/sec.
Zone D - 5.6 in/sec.
Zone E - 5.75 in/sec.

A.6.0 PREDICTION OF FLOW SPEEDS & RESIDENCE TIMES

Using the flow splits and recirculation rates from sections 3 and 4 and predicted airflow distribution from computer model of Class B flametube, the following information was obtained.

A.6.1 Approximate Distribution in Final Model

Table A.3 - Combustor Geometry

Flametube Component	Design Area of Port	Water Model Area	Design Flow	Model Flow (Predicted)
Swirler	.0456 in^2	.0703 in^2	.0246 lb/sec	.0379 lb/sec
Dome holes	.1247 in^2	.1247 in^2	.0910 lb/sec	.0910 lb/sec
Primary ports	.2945 in^2	.2945 in^2	.2123 lb/sec	.2123 lb/sec
IZ ports	.0373 in^2	.0373 in^2	.0272 lb/sec	.0272 lb/sec
DZ ports	.0496	.0506 in^2	.362 lb/sec	.3690 lb/sec
				Σ = .7374

Hence, % flows are:

Swirler	5.13%
Dome holes	12.34%
Prim ports	28.83%
IZ ports	3.70%
DZ ports	50.00%

Total design flow = 1.11 lbs/sec

∴ Flows under rig conditions of airflow, pressure and temperature, without fuel or heat release, would be as follows:

Swirler	.057 lbs/sec
Dome holes	.137 lbs/sec
Primary ports	.320 lbs/sec
DZ ports	.041 lbs/sec
DZ ports	.555 lbs/sec

A.6.2 Flows in Flametube Zones

Flow in Zone A (approach) = 1.11 lbs/sec.

Flow in Zone B (P. recirculation) = Swirler + Dome + 41.2% primary jet air = .057 + .137 + .132 = .326 lbs/sec.

Flow in Zone C (Post P.) = Zone B flow + 58.8% primary jet air = .326 + .188 = .514 lbs/sec.

Flow in Zone D (intermediate Zone) = Zone C flow + 1.2 ports flow + 47.3% 1st row dilution air = .514 + .041 +

$$+\left[.555\ \frac{(.188^2)}{(.188^2 + .21^2)} \times \frac{47.3}{100}\right] = \underline{.671\ \text{lbs/sec}}.$$

Flow in Zone E = Total flow = 1.11 lbs/sec.

A.6.3 Flow Speeds

Table A.4 - Flow Splits

Zone	Vmean Axial = W/PA ft/sec	Mean Flowpath length from photos - ins.	Mean Flowpath Axial length = R	# of times over flow-path (N)	Mean Speed = Vmean Axial x N x R ft/sec	Speed ÷ Speed for Zone A
A	27.02	-	1	1	27.02	1
B	15.6	2.75	2.22	2.7	93.5	3.46
C	24.6	1.25	1	1	24.6	.910
D	32.6	1.88	1.25	1.58	64.5	2.38
E	53.2	1.5	1	1	53.2	1.96

Comparative values of speed/speed (Zone A) from photographic traces are:

Zone A $= \frac{3.1}{3.1} = 1.0$

Zone B $= \frac{6.05}{3.1} = 1.95$

Zone C $= \frac{2.94}{3.1} = .95$

Zone D $= \frac{5.6}{3.1} = 1.81$

Zone E $= \frac{5.75}{3.1} = 1.85$

The estimated flow speeds for zones involving recirculation are considerably higher than those from the photographic traces. The initial statement in Section A.5 accounts for some of this difference but, nevertheless, it is felt that the photographic trace readings will be nearest the true value.

Hence, until better readings are obtained, the following values of speed/speed A will be quoted:

Zone A = 1.0
Zone B = 2.0
Zone C = 1.0
Zone D = 1.8
Zone E = 1.9

A.6.4 Residence Times

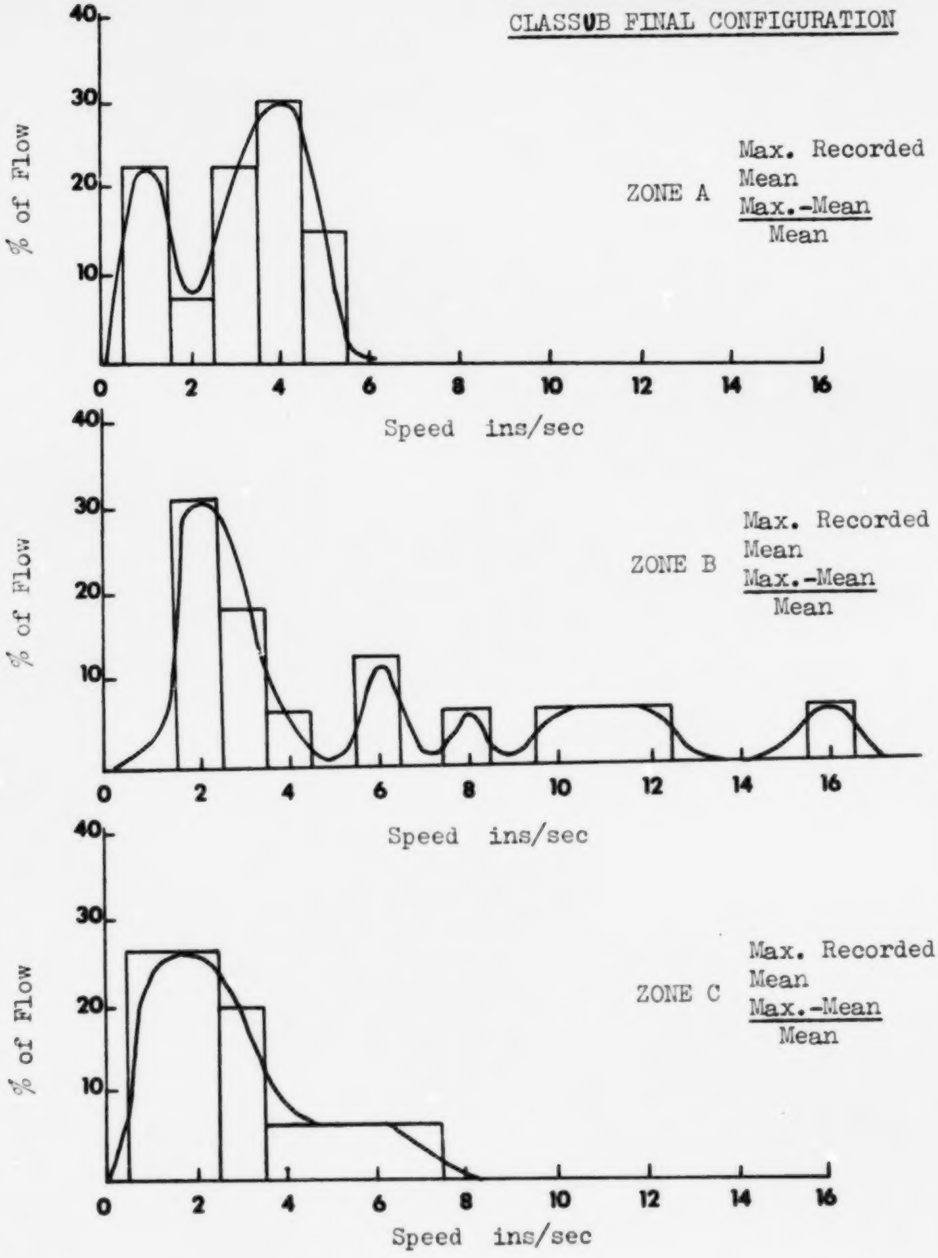
Estimated residence times are as follows:

Table A.5 - Residence Times

Zone	Vaxial ft/sec	Zone length ins.	Residence Time sec x 10^3
A	27.02	-	-
B	15.6	1.25	6.68
C	24.6	1.25	4.23
D	32.6	1.5	3.84
E	53.2	1.5	2.35

These values are for design conditions of air, with no heat release.

Figure A.3 - DISTRIBUTION OF FLOW SPEEDS IN WATER MODEL CLASSUB FINAL CONFIGURATION

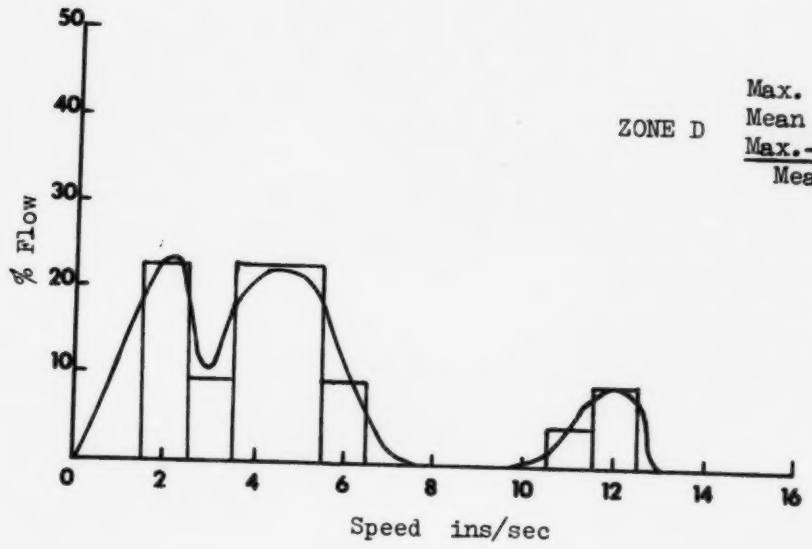


ZONE A
Max. Recorded = 4.75 in/sec
Mean = 3.1 in/sec
$\frac{\text{Max.-Mean}}{\text{Mean}}$ = .532

ZONE B
Max. Recorded = 16.25 in/sec
Mean = 6.05 in/sec
$\frac{\text{Max.-Mean}}{\text{Mean}}$ = 1.685

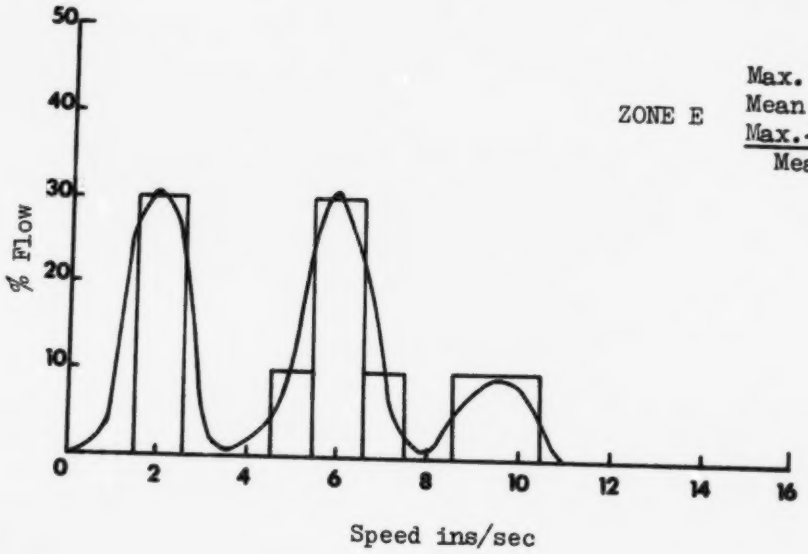
ZONE C
Max. Recorded = 7 in/sec
Mean = 2.94 in/sec
$\frac{\text{Max.-Mean}}{\text{Mean}}$ = 1.383

Figure A.4 - DISTRIBUTION OF FLOW SPEEDS IN WATER MODEL CLASS VB FINAL CONFIGURATION



ZONE D

Max. Recorded = 12.5 in/sec
Mean = 5.6 in/sec
$\frac{\text{Max.-Mean}}{\text{Mean}} = 1.23$



ZONE E

Max. Recorded = 10 in/sec
Mean = 5.75 in/sec
$\frac{\text{Max.-Mean}}{\text{Mean}} = .738$

APPENDIX B

COMPILATION OF COMBUSTOR CONFIGURATIONS AND TEST RESULTS

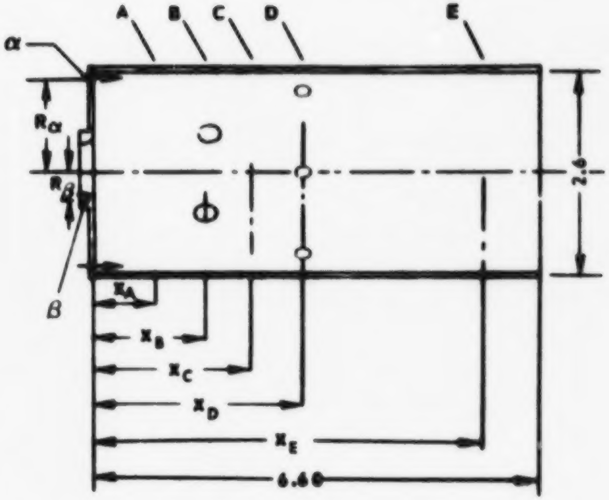
Tables B-1 through B-4 contain tabulations of the combustor configurations, test conditions, and emissions data obtained during the development and evaluation of the simple-cycle and regenerative-cycle combustors. The data compiled herein are organized according to combustor type and chronologically according to test number and combustor modification number. The data listed for each test consists of combustor geometry, fuel nozzle type, inlet air pressure, inlet air temperature, overall fuel-air ratio, combustor pressure loss, and emissions levels of NO_x, CO, and UHC. The codes describing the fuel nozzle type and air swirler geometry are explained in Tables B-5 and B-6.

Figure B-1 - Fuel flow vs fuel pressure drop for air blast atomizer.

Figure B-2 - Exit temperature distributions from final Class UB combustor configuration for Federal Driving Cycle Test Points.

TABLE B-1

SUMMARY OF SIMPLE-CYCLE (CLASS UB) COMBUSTOR CONFIGURATIONS



MOD	A			B			C			D			E			α			β			AIR SWIRLER
	Dia.	No	X_A	Dia.	No	X_B	Dia.	No	X_C	Dia.	No	X_D	Dia.	No	X_E	Dia.	No	R_α	Dia.	N	R_β	
0	.234	11	.83	.228	12	1.33	.213	12	1.83	.140	12	2.66	.266	8	4.0	—	-	—	—	—	—	—
1	.234	11	.83	.288	12	1.33	.213	12	1.83	.140	12	2.66	.266	8	4.0	—	-	—	.153	4	.65	—
2	.234	11	.83	.288	12	1.33	.213	12	1.83	.140	12	2.66	.266	8	4.0	.082	40	1.25	.153	4	.65	—
3	.234	11	.83	.288	12	1.33	.213	12	1.83	.140	12	2.66	.188	8	4.0	.082	40	1.25	.153	4	.65	—
4	—	—	—	.288	12	1.33	.213	12	1.83	.140	12	2.66	.266	8	4.0	.082	40	1.25	.153	4	.65	—
5	.234	6	.83	.228 Plunged 3/16	6	1.33	.213	12	1.83	.140	12	2.66	.188	8	4.88	.082	40	1.25	.153	4	.65	—

TABLE B-1 (cont.)

MOD	A			B			C			D			E			α			β			AIR SWIRLER
	Dia.	No	X_A	Dia.	No	X_B	Dia.	No	X_C	Dia.	No	X_D	Dia.	No	X_E	Dia.	No	R_α	Dia.	No	R_β	
6	.234	6	.83	.228	12	1.33	.213	12	1.83	—	—	—	.188	8	4.88	.082	40	1.25	.153	4	.65	—
7	.234	11	.83	.228	12	1.33	.213	12	1.83	.140	12	2.66	.188	8	4.88	.082 .092	40 12	1.25 .80	.153 direction reversed	4	.65	—
8	.234	6	.83	.228 Plunged 3/16	6	1.33	.213	12	1.83	—	—	—	.266	8	4.88	.082	40	1.25	.153	4	.65	—
9	.234	11	.83	.228 Plunged 3/16	12	1.33	.213 Plunged 3/16	12	1.83	.140	12	2.66	.188	8	4.88	.082 .092	40 12	1.25 .80	.153 direction reversed	4	.65	—
10	.166	11	.83	.228 Plunged 3/16	6	1.33	.213 Plunged 3/16	12	1.83	—	—	—	.266	8	4.88	.082	40	1.25	.153	4	.65	—
11	.166	11	.83	.228 Plunged 3/16	6	1.33	.151 Plunged 3/16	12	1.83	—	—	—	.266 .185	8 8	4.88 4.88	.082	40	1.25	.153	4	.65	—
59	.166	11	.83	.228 Plunged 3/16	6	1.33	.213 Plunged 3/16	12	1.83	—	—	—	.266 .185	8 8	4.88 4.88	.093	40	1.25	.153	4	.65	1
60	.166	11	.83	.228 Plunged 3/16	6	1.33	.213 Plunged 3/16	12	1.83	.209	8	4.40	.266 .185	8 8	4.88 4.88	.093	40	1.25	.153	4	.65	1
61	.166	11	.83	.228 Plunged 3/16	11	1.33	.213 Plunged 3/16	6	1.83	.209	8	4.40	.266 .185	8 8	4.88 4.88	.093	40	1.25	.153	4	.65	1
62	.166	11	.83	.228 Plunged 3/16	11	1.33	—	—	—	.209	8	4.40	.266 .185	8 8	4.88 4.88	.093	40	1.25	.153	4	.65	1
63	.166	11	.83	.161 Plunged 3/16	11	1.33	—	—	—	—	—	—	.272	16	4.88	.093	40	1.25	.153	4	.65	1
64	.166	11	.83	.161 Plunged 3/16	11	1.33	—	—	—	.209	8	4.40	.272	16	4.88	.093	40	1.25	.153	4	.65	1

TABLE B-1 (cont.)

MOD	A			B			C			D			F			α			β			AIR SWIRLER
	Dia.	No	X_A	Dia.	No	X_B	Dia.	No	X_C	Dia.	No	X_D	Dia.	No	X_F	Dia.	No	R_α	Dia.	No	R_β	
65	.166	11	.83	.161 Plunged	12	1.33 3/16	—	—	—	.209	8	4.40	.272	16	4.88	.082	40	1.25	.153	4	.65	1
66	.166	11	.83	.172 Plunged	12	1.33 3/16	—	—	—	.209	8	4.40	.272	16	4.88	.082	40	1.25	.153	4	.65	1
67	.166	11	.83	.165 Plunged	12	1.33 3/16	—	—	—	.209	8	4.40	.272	16	4.88	.082	40	1.25	.153	4	.65	1
68	.166	11	.83	.165 Plunged	12	1.33 3/16	—	—	—	.209	8	4.40	.272	16	4.88	.082	20	1.25	.153	4	.65	1
69	.166	11	.83	.165 Plunged	12	1.33 3/16	—	—	—	.209	8	4.40	.272	16	4.88	.082	20	1.25	.200	4	.65	1
70	.166	11	.83	.165 Plunged	12	1.33 3/16	—	—	—	.209	8	4.40	.272	16	4.88	.082	20	1.25	.200	4	.65	2
71	.166	11	.83	.165 Plunged	12	1.33 3/16	—	—	—	.209	8	4.40	.272	16	4.88	.082	20	1.25	.153	4	.65	2
72	.166	11	.83	—	—	—	—	—	—	.209 .199	8 8	4.40 4.40	.272	16	4.88	.082	20	1.25	.153	4	.65	2
73	.177	11	.83	—	—	—	—	—	—	.209 .199	8 8	4.40 4.40	.272	16	4.88	.082	20	1.25	.153	4	.65	2
74	.185	11	.83	—	—	—	—	—	—	.209 .199	8 8	4.40 4.40	.272	16	4.88	.082	20	1.25	.153	4	.65	2
75	.185	11	.83	—	—	—	—	—	—	.209 .199	8 8	4.40 4.40	.272	16	4.88	.082	20	1.25	.153	4	.65	3
76	.177	12	.83	—	—	—	—	—	—	.209 .199	8 8	5.60 5.60	.272	16	5.90	.082	20	1.25	.153	4	.65	3

TABLE B-1 (cont.)

MOD	A			B			C			D			E			α			β			AIR SWIRLER
	Dia.	No	X_A	Dia.	No	X_B	Dia.	No	X_C	Dia.	No	X_D	Dia.	No	X_E	Dia.	No	R_α	Dia.	No	R_β	
77	.177	12	.83	—	—	—	—	—	—	.209 .199	8 8	5.60 5.60	.272	16	5.90	.082	40	1.25	.153	4	.65	3
78	.187	12	.83	—	—	—	—	—	—	.209 .199	8 8	5.60 5.60	.272	16	5.90	.082	40	1.25	.153	4	.65	3
79	.187	12	.83	—	—	—	—	—	—	.209 .199	8 8	5.60 5.60	.272	16	5.90	.082	40	1.25	.153	4	.65	3
80	.187	12	.83	—	—	—	—	—	—	.209 .199	8 8	5.60 5.60	.272	16	5.90	.082	40	1.25	.153	4	.65	2
81	.187	12	.83	.062	12	1.33	—	—	—	.209 .199	8 8	5.60 5.60	.272	16	5.90	.082	40	1.25	.153	4	.65	2
82	.187	12	.83	—	—	—	—	—	—	.209 .199	8 8	5.60 5.60	.272	16	5.90	.082	40	1.25	.161	4	.65	2
83	.187	12	.83	—	—	—	—	—	—	.209 .199	8 8	5.60 5.60	.272	16	5.90	.082	40	1.25	.171	4	.65	2
84	.187	12	.83	—	—	—	—	—	—	.209 .199	8 8	5.60 5.60	.272	16	5.90	.082	20	1.25	.171	4	.65	2
85	.187	12	.83	.128	12	1.33	—	—	—	.209 .199	8 8	5.60 5.60	.272	16	5.90	.082	20	1.25	.171	4	.65	2
86	.132	24	.83	—	—	—	—	—	—	.209 .199	8 8	5.60 5.60	.272	16	5.90	.082	20	1.25	.171	4	.65	2
87	.132	24	.83	—	—	—	—	—	—	—	—	—	.272	16	5.90	.082	20	1.25	.171	4	.65	2
88	.132	24	.83	—	—	—	—	—	—	.144	16	5.60	.272	16	5.90	.082	20	1.25	.171	4	.65	2
89	.132	24	.83	—	—	—	—	—	—	.144	16	5.60	.272	16	5.90	.058	40	1.10	.171	4	.65	2

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TABLE B-1 (cont.)

MOD	A			B			C			D			E			α			β			AIR SWIRLER
	Dia.	No	X_A	Dia.	No	X_B	Dia.	No	X_C	Dia.	No	X_D	Dia.	No	X_E	Dia.	No	R_α	Dia.	No	R_β	
90	.132	24	.83	—	—	—	—	—	—	.144	16	5.60	.272	16	5.90	.062	40	1.10	.171	4	.65	2
91	.132	24	.60	—	—	—	—	—	—	.144	16	5.60	.272	16	5.90	.062	40	1.10	.171	4	.65	2
92	.132	24	.60	—	—	—	—	—	—	.204	16	5.60	.272	16	5.90	.062	40	1.10	.171	4	.65	2
93	—	—	—	—	—	—	—	—	—	.204	16	5.60	.272	16	5.90	.062	40	1.10	.171	4	.65	2
94	—	—	—	—	—	—	—	—	—	.204	16	5.60	.272	16	5.90	.062	40	1.10	.201	4	.65	2
95	—	—	—	.091	12	1.33	—	—	—	.204	16	5.60	.272	16	5.90	.062	40	1.10	.201	4	.65	2
96	—	—	—	.091	12	1.33	—	—	—	.204	16	5.60	.272	16	5.90	.062	40	1.10	.201	4	.65	4
97	—	—	—	.091	12	1.33	—	—	—	.204	16	5.60	.272	16	5.90	.062 .082	40 10	1.10 1.25	.201	4	.65	4
98	—	—	—	.091	24	1.33	—	—	—	.204	16	5.60	.272	16	5.90	.062	40	1.10	.201	4	.65	4
99	—	—	—	.091 .062	24 22	1.33 1.33	—	—	—	.204	16	5.60	.272	16	5.90	.062	40	1.10	.201	4	.65	4
100	—	—	—	.091 .062	24 22	1.33 1.33	—	—	—	.188	16	5.60	.272	16	5.90	.062	40	1.10	.201	4	.65	4
101	—	—	—	.062	22	1.33	—	—	—	.188	16	5.60	.272	16	5.90	.062	40	1.10	.201	4	.65	4
102	—	—	—	.062	22	1.33	—	—	—	.188	16	5.60	.272	16	5.90	.062	40	1.10	.205	4	.65	4
103	—	—	—	.062	22	1.33	—	—	—	.188	16	5.60	.272	16	5.90	.062 .040	40 12	1.10 .95	.205	4	.65	4
104	—	—	—	.062	22	1.33	—	—	—	.188	16	5.60	.272	16	5.90	.062 .040	40 20	1.10 .95	.205	4	.65	4

TABLE B-1 (cont.)

MOD	A			B			C			D			E			α			β			AIR SWIRLER
	Dia.	No	X_A	Dia.	No	X_B	Dia.	No	X_C	Dia.	No	X_D	Dia.	No	X_E	Dia.	No	R α	Dia.	No	R β	
105	—	—	—	.062	22	1.33	—	—	—	.144	16	5.60	.272	16	5.90	.062 .040	40 12	1.10 .95	.205	4	.65	4
106	—	—	—	.062	22	1.33	.040	144	1.5-2.25	.144	16	5.60	.272	16	5.90	.062 .040	40 20	1.10 .95	.201	4	.65	4
107	—	—	—	.062	22	1.33	.040	24	1.5	.177	16	5.60	.272	16	5.90	.062 .040	40 20	1.10 .95	.201	4	.65	4
108	—	—	—	—	—	—	.040	48	1.65-1.80	.177	16	5.60	.272	16	5.90	.062 .040	40 20	1.10 .95	.201	4	.65	4
109	—	—	—	—	—	—	.040	72	1.95-2.25	.177	16	5.60	.272	16	5.90	.062 .040	40 20	1.10 .95	.201	4	.65	4
110	—	—	—	.062	22	1.33	.040	24	1.5	.177	16	5.60	.272	16	5.90	.062 .040	40 12	1.10 .95	.201	4	.65	4
111	.025	48	.40-.60	—	—	—	.040	24	1.5	.177	16	5.60	.272	16	5.90	.062 .040	40 12	1.10 .95	.201	4	.65	4
112	.025	48	.60-.80	—	—	—	.040	24	1.5	.177	16	5.60	.272	16	5.90	.062 .040	40 12	1.10 .95	.201	4	.65	4
113	.025	48	.60-.80	—	—	—	.040	24	1.5	.177	16	5.60	.272	16	5.90	.062 .040	40 12	1.10 .95	.201	4	.65	2
114	.025	72	.20-.60	—	—	—	.040	24	1.5	.177	16	5.60	.272	16	5.90	.062 .040	40 12	1.10 .95	.201	4	.65	2
115	.025	120	.20-1.0	—	—	—	.040	24	1.5	.177	16	5.60	.272	16	5.90	.062 .040	40 12	1.10 .95	.201	4	.65	2
116	.025	96	.20-.80	—	—	—	.040	24	1.5	.177	16	5.60	.272	16	5.90	.062 .040	40 12	1.10 .95	.201	4	.65	2

TABLE β-1 (cont.)

MOD	A			B			C			D			E			α			β			AIR SWIRLER
	Dia.	No	X_A	Dia.	No	X_B	Dia.	No	X_C	Dia.	No	X_D	Dia.	No	X_E	Dia.	No	R_α	Dia.	No	R_β	
132	.091	24	.60	—	—	—	—	—	—	.144	16	5.60	.192	16	5.90	.062	40	1.10	.201	4	.65	2
133	.091	24	.60	—	—	—	—	—	—	.144	16	5.60	.192	16	5.90	—	—	—	.201	4	.65	2
134	.091	24	.60	—	—	—	—	—	—	.176	16	5.60	.192	16	5.90	—	—	—	.201	4	.65	2
135	.091	24	.60	—	—	—	—	—	—	.204	16	5.60	.192	16	5.90	—	—	—	.201	4	.65	2
136	.091	24	.60	—	—	—	—	—	—	.204	16	5.60	.192	16	5.90	—	—	—	.201	4	.65	4
137	.091	24	.60	—	—	—	—	—	—	.204	16	5.60	.236	16	5.90	—	—	—	.201	4	.65	4
138	.091	24	.60	—	—	—	—	—	—	.204	16	5.60	.272	16	5.90	—	—	—	.201	4	.65	4
139	.091	24	.60	—	—	—	.040	22	2.25	.204	16	5.60	.272	16	5.90	—	—	—	.201	4	.65	4
140	.091	24	.60	—	—	—	—	—	—	.204	16	5.60	.272	16	5.90	.040	12	.95	.201	4	.65	4
141	.091	24	.60	—	—	—	—	—	—	.204	16	5.60	.272	16	5.90	.040	20	.95	.201	4	.65	4
142	.089	24	.60	—	—	—	—	—	—	.204	16	5.60	.272	16	5.90	.040	12	.95	.173	4	.65	4
143	.089	24	.60	—	—	—	—	—	—	.194	16	5.60	.272	16	5.90	.040	12	.95	.173	4	.65	4
144	.089	24	.60	—	—	—	—	—	—	.194	16	5.60	.261	16	5.90	.040	12	.95	.173	4	.65	4
145	.089	24	.60	—	—	—	—	—	—	.194	16	5.60	.266	16	5.90	.040	12	.95	.173	4	.65	4
146	.089	24	.60	—	—	—	—	—	—	.181	16	5.60	.266	16	5.90	.040	12	.95	.173	4	.65	4
147	.089	24	.60	—	—	—	—	—	—	.1815	16	5.60	.266	16	5.90	.040	12	.95	.173	4	.65	4
148	.089	24	.60	—	—	—	—	—	—	.182	16	5.60	.266	16	5.90	.040	12	.95	.173	4	.65	4

TABLE B-2
SUMMARY OF TEST DATA FROM SIMPLE-CYCLE (CLASS UB) COMBUSTOR
(ZERO HUMIDITY)

Test No./ Fuel Nozzle/ Combustor Mod	Inlet Air Pressure	Inlet Air Temp.	Combustor Pressure Loss	Fuel-Air Ratio	Pollutant Emissions								
					NO_x (NO_2)			CO			UHC (C_6H_{14})		
	psig	F	$\frac{Pin - Pout}{Pin}$ x100		ppm	EI	g/mi*	ppm	EI	g/mi*	ppm C	EI	g/mi*
7/AB/0	53.0	465.0	—	0.0104	21.7	3.36	1.125	362.0	34.14	11.43	59.0	2.85	0.955
8/AB/0	46.0	425.0	—	0.0071	13.6	3.06	1.026	276.0	37.86	12.67	49.0	3.45	1.154
9/AA/0	53.0	455.0	—	0.0104	20.2	3.115	1.043	460.0	43.19	14.46	49.0	2.36	0.790
10/AA/0	47.0	425.0	—	0.0081	15.5	3.075	1.029	349.0	42.16	14.11	26.0	1.61	0.539
11/AA/0	46.0	425.0	—	0.0083	16.6	3.19	1.068	393.0	46.02	15.41	26.0	1.56	0.522
12/AA/0	53.0	460.0	—	0.0118	23.2	3.16	1.059	488.0	40.50	13.56	56.0	2.38	0.798
13/PA1/0	46.0	420.0	—	0.0062	16.5	4.268	1.429	350.0	55.20	18.48	38.0	3.069	1.027
14/PA1/0	53.0	460.0	—	0.0098	26.0	4.280	1.433	382.0	38.31	12.83	18.0	0.925	0.310
15/AA/1	46.0	425.0	—	0.0069	16.0	3.71	1.24	322.0	46.94	15.72	55.0	3.985	1.33
17/AA/1	53.0	460.0	—	0.0096	22.3	3.76	1.260	368.0	37.74	12.63	46.0	2.42	0.81
18/AA/1	46.0	425.0	—	0.0068	17.0	4.05	1.350	283.0	41.03	13.73	38.0	2.82	0.95
19/AA/2	46.0	425.0	—	0.0068	16.00	3.795	1.27	456.0	65.86	22.05	115.0	8.510	2.850
20/AA/2	53.0	460.0	—	0.0091	22.25	3.940	1.32	419.0	45.22	15.14	25.0	1.382	0.463
21/AB/3	53.0	460.0	—	0.0087	22.00	4.05	1.356	540.0	60.56	20.27	155.0	8.91	2.98
22/AB/3	46.0	425.0	—	0.0065	15.75	3.88	1.298	592.0	88.77	29.72	445.0	34.20	11.45

* Vehicle Fuel Economy = 8.6 miles/gal

TABLE B-2 (cont.)

Test No./ Fuel Nozzle/ Combustor Mod	Inlet Air Pressure	Inlet Air Temp.	Combustor Pressure Loss	Fuel-Air Ratio	Pollutant Emissions								
					NO_x (NO_2)			CO			UHC (C_6H_{14})		
	psig	F	$\frac{Pin - Pout}{Pin}$ x100		ppm	EI	g/mi*	ppm	EI	g/mi*	ppm C	EI	g/mi*
23/PA1/3	53.0	425.0	—	0.0094	22.5	3.875	1.297	540.0	56.58	18.94	235.0	12.63	4.229
24/PA1/3	46.0	425.0	—	0.0064	15.5	3.882	1.300	543.0	82.80	27.72	265.0	20.72	6.937
30/AB/0	46.0	425.0	—	0.0069	12.75	2.977	0.997	395.1	56.16	18.80	260.0	18.95	6.344
31/AB/0	53.0	460.0	—	0.0099	24.5	3.995	1.337	299.7	29.76	9.962	41.0	2.087	0.699
32/AA/0	46.0	425.0	—	0.0073	13.75	3.010	1.008	358.3	47.75	15.99	40.0	2.734	0.915
33/AA/0	53.0	460.0	—	0.0106	23.50	3.578	1.198	393.0	36.43	12.19	25.0	1.188	0.398
34/AA/3	46.0	425.0	—	0.0073	14.0	3.065	1.026	493.9	65.83	22.04	300.0	20.50	6.864
35/AA/3	53.0	460.0	—	0.0106	21.0	3.197	1.070	441.5	40.93	13.70	24.0	1.141	0.382
38/AA/2	46.0	425.0	—	0.0073	5.50	1.212	0.406	325.7	43.70	14.63	130.0	8.946	2.994
39/AA/2	53.0	460.0	—	0.0103	9.00	1.408	0.472	363.0	34.58	11.58	87.0	4.25	1.423
40/AA/4	47.0	425.0	—	0.0073	7.25	1.598	0.535	340.3	45.67	15.29	66.00	4.542	1.520
41/AA/4	53.0	460.0	—	0.0102	4.50	0.713	0.239	490.4	47.32	15.84	130.0	6.432	2.153
42/AA/4	46.0	425.0	—	0.0072	6.75	1.500	0.502	330.6	44.73	14.98	36.00	2.498	0.836
43/AA/4	53.0	460.0	—	0.0103	5.50	0.857	0.287	475.7	45.16	15.12	—	—	—

TABLE B-2 (cont.)

Test No./ Fuel Nozzle/ Combustor Mod	Inlet Air Pressure	Inlet Air Temp.	Combustor Pressure Loss	Fuel-Air Ratio	Pollutant Emissions								
					NO_x (NO_2)			CO			UHC (C_6H_{14})		
	psig	F	$\frac{P_{in} - P_{out}}{P_{in}} \times 100$		ppm	EI	g/mi*	ppm	EI	g/mi*	ppm C	EI	g/mi*
44/AA/3	46.0	427.0	—	0.0062	3.50	0.909	0.304	394.7	62.42	20.90	—	—	—
45/AA/3	53.0	460.0	—	0.0102	7.25	1.141	0.382	431.2	41.32	13.83	—	—	—
46/AA/5	46.0	425.0	—	0.0072	4.50	0.999	0.334	369.9	49.98	16.73	—	—	—
47/AA/5	53.0	460.0	—	0.0103	9.50	1.482	0.496	279.3	26.54	8.884	—	—	—
48/AA/6	.0	425.0	—	0.0073	1.80	0.397	0.133	493.4	66.21	22.17	—	—	—
49/A	53.0	457.0	—	0.0103	10.0	1.572	0.526	364.0	34.85	11.67	—	—	—
50/PA2/6	46.0	425.0	—	0.0072	2.50	0.559	0.187	425.1	57.85	19.36	—	—	—
51/PA2/6	53.0	460.0	—	0.0084	3.50	0.669	0.224	360.4	41.92	14.03	—	—	—
52/AA/7	46.0	425.0	—	0.0073	5.00	1.104	0.370	439.3	59.04	19.77	—	—	—
53/AA/7	53.0	450.0	—	0.0104	13.00	2.015	0.675	490.4	46.29	15.50	—	—	—
54/AA/8	46.0	425.0	—	0.0072	5.00	1.119	0.375	346.3	47.18	15.80	82.0	57.28	19.18
55/AA/8	53.0	460.0	—	0.0104	11.50	1.789	0.599	325.0	30.79	10.31	40.0	19.43	0.65
56/AA/9	46.0	425.0	—	0.0072	2.50	0.555	0.186	454.9	61.47	20.58	165.0	11.43	3.827
57/AA/9	53.0	457.0	—	0.0099	7.00	1.136	0.380	491.9	48.60	16.27	170.0	8.612	2.883
58/AA/10	46.0	425.0	—	0.0073	3.50	0.776	0.260	311.7	42.06	14.08	—	—	—
59/AA/10	53.0	460.0	—	0.0102	5.25	0.830	0.278	313.5	30.16	10.10	—	—	—
60/AA/11	46.0	425.0	—	0.0073	4.00	0.879	0.294	291.9	39.06	13.08	—	—	—
61/AA/11	53.0	460.0	—	0.0102	12.00	1.889	0.632	236.1	22.62	7.574	—	—	—

TABLE B-2 (cont.)

Test No./ Fuel Nozzle/ Combustor Mod	Inlet Air Pressure	Inlet Air Temp.	Combustor Pressure Loss	Fuel-Air Ratio	Pollutant Emissions								
					NO$_x$ (NO$_2$)			CO			UHC (C$_6$H$_{14}$)		
	psig	F	$\frac{\text{Pin - Pout}}{\text{Pin}}$ x100		ppm	EI	g/mi*	ppm	EI	g/mi*	ppm C	EI	g/mi*
186/DAA/59	53.0	457.0	2.5	0.0102	8.25	1.300	0.435	277.0	26.57	8.894	110.0	5.410	1.811
187/DAA/59	46.0	425.0	2.6	0.0073	3.50	0.774	0.259	324.1	43.61	14.60	110.0	7.590	2.541
188/DAA/60	53.0	460.0	2.1	0.0104	14.25	2.217	0.742	236.8	22.43	7.508	24.0	1.166	0.390
189/DAA/60	46.0	425.0	2.1	0.0074	8.75	1.898	0.635	256.1	33.82	11.32	27.0	1.828	0.612
190/DAA/61	53.0	465.0	2.0	0.0104	12.75	1.980	0.663	268.8	25.42	8.508	47.0	2.279	0.763
191/DAA/61	46.0	427.0	2.0	0.0074	5.90	1.290	0.432	347.5	46.26	15.49	72.0	4.915	1.645
192/DAA/62	53.0	460.0	2.3	0.0104	13.5	2.091	0.699	247.0	23.29	7.796	21.0	1.015	0.340
193/DAA/62	46.0	430.0	2.4	0.0074	5.5	1.188	0.398	348.2	45.79	15.33	37.0	2.495	0.835
194/DAA/63	53.0	460.0	2.7	0.0105	13.75	2.109	0.706	205.0	19.14	6.408	25.0	1.197	0.401
195/DAA/63	46.0	425.0	2.8	0.0073	3.20	0.708	0.237	345.7	46.59	15.60	73.0	5.044	1.689
196/DAA/64	53.0	460.0	2.2	0.0104	13.75	2.127	0.712	153.2	14.43	4.830	23.0	1.111	0.372
197/DAA/64	46.0	425.0	2.3	0.0074	5.30	1.157	0.387	230.1	30.59	10.24	34.0	2.318	0.776
198/DAA/65	53.0	460.0	2.4	0.0104	15.75	2.450	0.820	127.7	12.09	4.049	15.0	0.728	0.244
199/DAA/65	46.0	425.0	2.5	0.0073	7.50	1.653	0.553	186.7	25.06	8.388	29.0	1.995	0.668

TABLE B-2 (cont.)

Test No./ Fuel Nozzle/ Combustor Mod	Inlet Air Pressure	Inlet Air Temp.	Combustor Pressure Loss	Fuel-Air Ratio	Pollutant Emissions								
					NO_x (NO_2)			CO			UHC (C_6H_{14})		
	psig	F	$\frac{Pin - Pout}{Pin}$ x100		ppm	EI	g/mi*	ppm	EI	g/mi*	ppm C	EI	g/mi*
200/DAA/66	53.0	460.0	2.4	0.0104	17.5	2.707	0.906	112.9	10.63	3.559	18.0	0.869	0.291
201/DAA/66	46.0	425.0	2.4	0.0074	7.5	1.631	0.546	163.0	21.58	7.224	27.0	1.833	0.614
202/DAA/66	53.0	460.0	2.3	0.0104	10.25	1.590	0.532	171.9	16.23	5.435	110.0	5.327	1.783
203/DAA/66	46.0	425.0	2.4	0.0073	3.80	0.832	0.279	278.6	37.14	12.43	130.0	8.885	2.974
204/DAA/66	53.0	463.0	2.3	0.0104	10.0	1.551	0.519	162.1	15.31	5.127	140.0	6.780	2.270
205/DAA/66	46.0	425.0	2.4	0.0074	2.8	0.609	0.204	290.6	38.47	12.88	200.0	13.58	4.545
206/DAA/67	53.0	460.0	2.3	0.0103	15.0	2.345	0.785	149.2	14.20	4.754	23.0	1.122	0.376
207/DAA/67	46.0	425.0	2.4	0.0073	4.6	1.010	0.338	290.3	38.80	12.99	58.0	3.975	1.331
208/DAA/68	53.0	460.0	2.7	0.0103	12.65	1.974	0.661	106.9	10.16	3.400	16.2	0.789	0.264
209/DAA/68	46.0	425.0	2.8	0.0073	4.00	0.881	0.295	236.9	31.75	10.63	89.6	6.157	2.061
210/DAA/69	53.0	460.0	2.7	0.0104	11.98	1.864	0.624	111.9	10.59	3.547	72.2	3.507	1.174
211/DAA/69	46.0	425.0	2.6	0.0073	3.12	0.685	0.229	265.6	35.49	11.88	92.8	6.360	2.129
212/DAA/70	53.0	460.0	2.4	0.0104	11.6	1.798	0.602	105.5	9.951	3.331	95.8	4.635	1.552
213/DAA/70	46.0	425.0	2.6	0.0074	1.98	0.428	0.143	302.1	39.78	13.32	88.8	5.996	2.007

TABLE B-2 (cont.)

Test No./ Fuel Nozzle/ Combustor Mod	Inlet Air Pressure	Inlet Air Temp.	Combustor Pressure Loss	Fuel-Air Ratio	Pollutant Emissions								
					NO_x (NO_2)			CO			UHC (C_6H_{14})		
	psig	F	$\frac{Pin - Pout}{Pin}$ x100		ppm	EI	g/mi*	ppm	EI	g/mi*	ppm C	EI	g/mi*
214/DAA/T1	53.0	460.0	2.5	0.0105	11.50	1.772	0.593	109.4	10.27	3.437	93.0	4.474	1.498
215/DAA/T1	46.0	425.0	2.6	0.0075	2.44	0.524	0.176	300.2	39.27	13.15	100.2	6.721	2.250
216/DAA/T1	—	—	—	—	—	—	—	—	—	—	—	—	—
217/DAA/T1	53.0	460.0	2.6	0.01032	11.28	1.762	0.590	139.4	13.26	4.437	75.2	3.666	1.227
218/DAA/T1	46.0	425.0	2.7	0.0073	3.88	0.858	0.287	262.7	35.34	11.83	99.2	6.845	2.291
219/DAA/T2	53.0	460.0	2.7	0.0104	22.70	3.528	1.181	22.07	2.089	0.699	25.8	1.252	0.419
220/DAA/T2	46.0	425.0	2.7	0.0073	11.65	2.554	0.855	72.53	9.680	3.241	20.2	1.382	0.463
221/DAA/T3	53.0	455.0	2.7	0.0104	19.65	3.054	1.022	22.57	2.135	0.715	40.4	1.960	0.656
222/DAA/T3	46.0	425.0	2.9	0.0073	10.20	2.254	0.755	88.80	11.95	4.000	26.0	1.794	0.601
223/DAA/T4	53.0	455.0	2.7	0.0104	24.05	3.742	1.253	22.07	2.091	0.700	20.8	1.010	0.338
224/DAA/T4	46.0	425.0	2.8	0.0073	10.15	2.228	0.746	108.5	14.51	4.856	16.8	1.151	0.385
225/DAA/T5	53.0	460.0	2.7	0.0103	22.60	3.533	1.183	26.97	2.567	0.859	39.2	1.913	0.640
226/DAA/T5	46.0	425.0	2.834	0.0073	8.60	1.885	0.631	123.4	16.47	5.513	28.8	1.971	0.660

TABLE B-2 (cont.)

Test No./ Fuel Nozzle/ Combustor Mod	Inlet Air Pressure	Inlet Air Temp.	Combustor Pressure Loss	Fuel-Air Ratio	Pollutant Emissions								
					NO_x (NO_2)			CO			UHC (C_6H_{14})		
	psig	F	$\frac{Pin - Pout}{Pin}$ x100		ppm	EI	g/mi*	ppm	EI	g/mi*	ppm C	EI	g/mi*
227/DAA/76	53.0	455.0	3.043	0.0104	32.75	5.066	1.696	8.82	0.831	0.278	2.2	0.106	0.036
228/DAA/76	46.0	425.0	3.3	0.0074	15.7	3.414	1.143	12.73	1.685	0.564	2.4	0.163	0.055
229/DAA/76	53.0	455.0	3.2	0.0104	32.1	4.984	1.669	8.83	0.835	0.279	1.52	0.074	0.025
230/DAA/77	53.0	455.0	2.9	0.0103	25.85	4.033	1.350	6.86	0.652	0.218	1.6	0.078	0.026
231/DAA/77	46.0	425.0	3.1	0.0073	14.40	3.183	1.065	80.42	10.82	3.622	2.3	0.159	0.053
232/DAA/78	53.0	455.0	2.7	0.0103	25.75	4.029	1.349	9.81	0.934	0.313	2.0	0.098	0.033
233/DAA/78	46.0	425.0	2.9	0.0073	12.20	2.682	0.898	132.3	17.70	5.926	3.7	0.254	0.085
234/DAA/79	53.0	460.0	2.7	0.0104	24.75	3.850	1.289	6.86	0.650	0.218	2.15	0.104	0.035
235/DAA/79	46.0	425.0	2.9	0.0074	14.40	3.136	1.050	104.6	13.86	4.641	3.22	0.219	0.073
236/DAA/80	53.0	460.0	2.7	0.0104	23.10	3.580	1.198	9.81	0.926	0.310	3.80	0.184	0.062
237/DAA/80	46.0	425.0	2.8	0.0073	13.05	2.872	0.962	129.3	17.32	5.799	4.55	0.313	0.105
238/DAA/81	53.0	460.0	2.6	0.0104	23.8	3.706	1.241	9.32	0.883	0.296	1.55	0.075	0.025
239/DAA/81	46.0	425.0	2.8	0.0074	11.7	2.534	0.848	156.4	20.62	6.903	5.25	0.355	0.119
240/DAA/82	53.0	459.0	2.7	0.0104	23.35	3.605	1.207	10.79	1.015	0.340	2.56	0.123	0.041
241/DAA/82	46.0	425.0	2.8	0.0074	11.90	2.588	0.866	129.3	17.12	5.730	4.66	0.316	0.106

TABLE B-2 (cont.)

Test No./ Fuel Nozzle/ Combustor Mod	Inlet Air Pressure	Inlet Air Temp.	Combustor Pressure Loss	Fuel-Air Ratio	Pollutant Emissions								
					NO_x (NO_2)			CO			UHC (C_6H_{14})		
	psig	F	$\frac{Pin - Pout}{Pin}$ x100		ppm	EI	g/mi*	ppm	EI	g/mi*	ppm C	EI	g/mi*
242/DAA/83	53.0	458.0	2.6	0.0104	24.45	3.800	1.272	11.28	1.068	0.358	1.75	0.085	0.028
243/DAA/83	46.0	425.0	2.7	0.0074	10.75	2.350	0.787	149.0	19.84	6.641	6.10	0.416	0.139
244/DAA/84	53.0	456.0	3.0	0.0104	28.90	4.488	1.502	8.82	0.834	0.279	1.6	0.078	0.026
245/DAA/84	46.0	424.0	3.1	0.0074	13.55	2.962	0.992	66.11	8.799	2.946	3.4	0.232	0.078
246/DAA/85	53.0	456.0	2.6	0.0104	27.25	4.239	1.419	18.64	1.765	0.591	1.7	0.083	0.028
247/DAA/85	46.0	425.0	2.8	0.0073	12.25	2.689	0.900	98.69	13.19	4.415	5.0	0.343	0.115
248/DAA/86	53.0	455.0	2.9	0.0103	23.4	3.668	1.228	6.38	0.609	0.204	1.3	0.064	0.021
249/DAA/86	46.0	425.0	3.0	0.0074	15.6	3.410	1.142	75.99	10.11	3.386	2.3	0.157	0.053
250/DAA/87	53.0	460.0	4.8	0.0104	21.35	3.315	1.110	82.38	7.788	2.607	1.3	0.063	0.021
251/DAA/87	46.0	425.0	4.9	0.0073	2.24	0.495	0.166	32.70	52.58	17.60	390.7	2.257	0.755
252/DAA/88	53.0	460.0	3.6	0.0105	25.00	3.849	1.288	21.57	2.022	0.677	2.200	0.106	0.035
253/DAA/88	46.0	425.0	3.7	0.0074	10.50	2.277	0.762	191.4	25.28	8.462	3.900	0.264	0.088
254/DAA/89	53.0	458.0	3.5	0.0104	20.85	3.228	1.081	20.59	1.941	0.650	0.86	0.042	0.014
255/DAA/89	46.0	425.0	3.6	0.0073	7.15	1.567	0.525	209.2	27.92	9.348	7.15	0.489	0.164

TABLE B-2 (cont.)

Test No./ Fuel Nozzle/ Combustor Mod	Inlet Air Pressure	Inlet Air Temp.	Combustor Pressure Loss	Fuel-Air Ratio	Pollutant Emissions								
					NO_x (NO_2)			CO			UHC (C_6H_{14})		
	psig	F	$\frac{Pin - Pout}{Pin}$ x100		ppm	EI	g/mi*	ppm	EI	g/mi*	ppm C	EI	g/mi*
256/DAA/90	53.0	460.0	3.4	0.0103	21.05	3.294	1.103	27.46	2.616	0.876	0.82	0.040	0.013
257/DAA/90	46.0	425.0	3.5	0.0074	8.90	1.946	0.651	230.9	30.74	10.29	5.20	0.355	0.119
258/DAA/90	53.0	457.0	3.4	0.0104	22.05	3.430	1.148	23,53	2.229	0.746	2.200	0.107	0.036
259/DAA/90	46.0	425.0	3.5	0.0074	7.35	1.598	0.535	240.7	31.87	10.67	9.400	0.638	0.214
260/DAA/91	53.0	460.0	3.6	0.0104	21.75	3.364	1.126	9.313	0.877	0.294	0.900	0.043	0.015
261/DAA/91	46.0	424.0	3.6	0.0074	4.680	1.015	0.340	329.4	43.50	14.56	11.30	0.765	0.256
262/DAA/91	46.0	423.0	3.7	0.0073	4.040	0.891	0.298	354.1	47.53	15.91	11:70	0.805	0.270
263/DAA/91	53.0	460.0	3.6	0.0103	20.90	3.261	1.092	10.79	1.025	0.343	0.700	0.034	0.011
264/DAA/92	53.0	460.0	3.5	0.0105	40.28	6.202	2.076	14.11	1.322	0.443	3.400	0.163	0.055
265/DAA/92	46.0	424.0	3.7	0.0074	6.110	1.325	0.444	354.0	46.75	15.65	25.50	1.727	0.578
266/DAA/93	46.0	425.0	3.9	0.0074	21.85	4.719	1.580	4.929	0.648	0.2170	2.200	0.148	0.050
267/DAA/93	53.0	460.0	3.752	0.0104	49.90	7.712	2.582	32.82	3.088	1.034	1.200	0.058	0.019
268/DAA/94	53.0	456.0	3.6	0.0104	51.00	7.927	2.654	24.00	2.271	0.760	1.150	0.056	0.019
269/DAA/94	46.0	425.0	3.9	0.0075	20.55	4.433	1.484	10.35	1.360	0.455	1.400	0.094	0.032

TABLE B-2 (cont.)

Test No./ Fuel Nozzle/ Combustor Mod	Inlet Air Pressure	Inlet Air Temp.	Combustor Pressure Loss	Fuel-Air Ratio	Pollutant Emissions								
					NO_x (NO_2)			CO			UHC (C_6H_{14})		
	psig	F	$\frac{Pin - Pout}{Pin}$ x100		ppm	EI	g/mi*	ppm	EI	g/mi*	ppm C	EI	g/mi*
270/DAA/95	53.0	458.0	3.3	0.0104	32.20	5.005	1.675	11.76	1.113	0.373	0.800	0.039	0.013
271/DAA/95	46.0	425.0	3.4	0.0073	15.40	3.371	1.129	12.33	1.643	0.550	1.500	0.103	0.034
272/DAA/96	53.0	456.0	3.2	0.0104	29.15	4.501	1.507	8.333	0.783	0.262	1.300	0.063	0.021
273/DAA/96	46.0	425.0	3.3	0.0075	13.90	2.994	1.002	30.58	4.010	1.343	1.300	0.087	0.029
274/DAA/97	53.0	460.0	3.0	0.0104	28.27	4.381	1.467	5.392	0.509	0.170	1.800	0.087	0.029
275/DAA/97	46.0	425.0	3.2	0.0074	13.20	2.874	0.962	68.06	9.022	3.020	4.000	0.272	0.091
276/DAA/98	53.0	463.0	2.9	0.0105	25.70	3.960	1.326	4.412	0.414	0.139	1.600	0.077	0.026
277/DAA/98	46.0	428.0	3.2	0.0074	12.88	2.808	0.940	59.20	7.858	2.631	2.100	0.143	0.048
278/DAA/99	53.0	460.0	2.8	0.0104	23.06	3.574	1.196	3.922	0.370	0.124	1.400	0.068	0.023
279/DAA/99	46.0	425.0	3.0	0.0074	13.24	2.879	0.964	86.33	11.43	3.826	2.800	0.190	0.064
280/DAA/100	53.0	463.0	3.0	0.0104	22.50	3.490	1.168	3.922	0.370	0.124	0.900	0.044	0.015
281/DAA/100	46.0	423.0	3.1	0.0075	10.65	2.297	0.769	128.3	16.85	5.639	4.900	0.330	0.111
282/DAA/101	53.0	462.0	3.5	0.0104	27.10	4.216	1.411	6.866	0.650	0.218	2.100	0.102	0.034
283/DAA/101	46.0	422.0	3.6	0.0074	12.95	2.820	0.944	28.61	3.793	1.270	2.500	0.170	0.057

TABLE B-2 (cont.)

Test No./ Fuel Nozzle/ Combustor Mod	Inlet Air Pressure	Inlet Air Temp.	Combustor Pressure Loss	Fuel-Air Ratio	Pollutant Emissions								
					NO_x (NO_2)			CO			UHC (C_6H_{14})		
	psig	F	$\frac{Pin - Pout}{Pin}$ x100		ppm	EI	g/mi*	ppm	EI	g/mi*	ppm C	EI	g/mi*
284/DAA/102	53.0	460.0	3.5	0.0104	27.35	4.255	1.424	10.80	1.023	0.342	7.00	0.340	0.114
285/DAA/102	46.0	425.0	3.7	0.0074	13.35	2.903	0.972	28.13	3.724	1.247	2.100	0.143	0.048
286/DAA/103	53.0	460.0	3.5	0.0104	26.76	4.159	1.392	7.363	0.697	0.233	1.300	0.063	0.021
287/DAA/103	46.0	425.0	3.6	0.0073	11.07	2.430	0.814	63.21	8.447	2.828	3.500	0.240	0.080
288/DAA/104	53.0	460.0	3.4	0.0104	28.45	4.413	1.477	6.37	0.695	0.233	1.300	0.049	0.016
289/DAA/104	46.0	422.0	3.5	0.0073	10.36	2.274	0.761	115.9	15.49	5.186	8.400	0.576	0.193
290/DAA/105	53.0	460.0	4.1	0.0106	23.48	3.558	1.191	5.873	0.542	0.181	1.500	0.071	0.024
291/DAA/105	46.0	429.0	4.4	0.0074	7.09	1.540	0.516	182.4	24.11	8.073	8.900	0.603	0.202
292/DAA/106	53.0	453.0	3.3	0.0104	23.60	3.672	1.229	23.53	2.229	0.746	1.900	0.092	0.031
293/DAA/106	46.0	425.0	3.5	0.0074	2.220	0.485	0.162	468.7	62.31	20.86	65.30	4.452	1.490
294/DAA/107	53.0	460.0	3.3	0.0104	24.00	3.730	1.249	15.69	1.484	0.497	10.20	0.495	0.166
295/DAA/107	46.0	425.0	3.4	0.0074	8.540	1.857	0.622	179.5	23.77	7.956	22.60	1.534	0.514
296/DAA/108	53.0	460.0	3.2	0.0104	34.05	5.297	1.773	8.820	0.835	0.280	2.150	0.104	0.035
297/DAA/108	46.0	425.0	3.4	0.0074	10.33	2.246	0.752	199.5	26.41	8.841	16.10	1.093	0.366

TABLE B-2 (cont.)

Test No./ Fuel Nozzle/ Combustor Mod	Inlet Air Pressure	Inlet Air Temp.	Combustor Pressure Loss	Fuel-Air Ratio	Pollutant Emissions								
					NO_x (NO_2)			CO			UHC (C_6H_{14})		
	psig	F	$\frac{Pin - Pout}{Pin}$ x100		ppm	EI	g/mi*	ppm	EI	g/mi*	ppm C	EI	g/mi*
298/DAA/108	53.0	457.0	3.3	0.0104	33.95	5.272	1.765	6.870	0.650	0.217	0.700	0.034	0.011
299/DAA/108	46.0	425.0	3.5	0.0074	11.93	2.594	0.669	153.0	20.25	6.781	9.200	0.625	0.209
300/DAA/109	53.0	460.0	3.3	0.0103	35.94	5.607	1.877	7.353	0.699	0.234	0.600	0.029	0.010
301/DAA/109	46.0	425.0	3.4	0.0075	10.82	2.334	0.781	160.8	21.12	7.071	9.300	0.626	0.210
302/DAA/110	53.0	460.0	3.2	0.0104	29.66	4.614	1.545	7.341	0.695	0.233	1.000	0.049	0.016
303/DAA/110	46.0	425.0	3.2	0.0074	12.64	2.763	0.925	87.68	11.67	3.907	3.460	0.236	0.079
304/DAA/111	53.0	455.0	3.5	0.0104	20.02	3.109	1.041	58.83	5.562	1.862	101.0	4.896	1.639
305/DAA/111	46.0	423.0	3.7	0.0074	4.780	1.044	0.349	105.6	14.03	4.698	99.20	6.761	2.263
306/DAA/112	53.0	460.0	3.2	0.0104	29.56	4.586	1.535	49.92	4.715	1.579	54.40	2.635	0.882
307/DAA/112	46.0	425.0	3.5	0.0074	6.960	1.511	0.506	89.75	11.87	3.972	58.90	3.993	1.337
308/DAA/113	53.0	460.0	3.5	0.0104	27.64	4.280	1.433	46.54	4.387	1.469	67.20	3.248	1.087
309/DAA/113	46.0	425.0	3.7	0.0074	7.420	1.616	0.541	61.18	8.110	2.715	73.20	4.976	1.666
310/DAA/111	53.0	460.0	3.5	0.0104	37.20	5.760	1.928	9.804	0.924	0.309	1.200	0.058	0.019
311/DAA/111	53.0	460.0	3.5	0.0104	36.54	5.685	1.903	9.803	0.929	0.311	1.000	0.049	0.016
312/DAA/111	46.0	425.0	3.6	0.0075	11.22	2.420	0.810	67.07	8.809	2.949	8.250	0.556	0.186

TABLE B-2 (cont.)

Test No./ Fuel Nozzle/ Combustor Mod	Inlet Air Pressure	Inlet Air Temp.	Combustor Pressure Loss	Fuel-Air Ratio	Pollutant Emissions								
					NO_x (NO_2)			CO			UHC (C_6H_{14})		
	psig	F	$\frac{Pin - Pout}{Pin}$ x100		ppm	EI	g/mi*	ppm	EI	g/mi*	ppm C	EI	g/mi*
313/DAA/113	53.0	463.0	3.6	0.0104	38.40	5.951	1.992	13.23	1.249	0.418	0.600	0.029	0.010
314/DAA/113	46.0	425.0	3.8	0.0074	16.88	3.675	1.230	35.02	4.643	1.554	1.700	0.116	0.039
315/DAA/111	53.0	455.0	3.3	0.0104	36.50	5.678	1.901	14.70	1.393	0.466	0.700	0.034	0.011
316/DAA/111	46.0	429.0	3.4	0.0074	9.86	2.144	0.718	181.0	23.96	8.021	29.30	1.989	0.666
317/DAA/111	53.0	456.0	3.7	0.0104	37.76	5.847	1.957	9.801	0.924	0.309	0.900	0.044	0.015
318/DAA/111	46.0	423.0	3.8	0.0074	13.02	2.831	0.948	31.56	4.178	1.399	1.700	0.115	0.039
319/DAA/114	53.0	458.0	3.5	0.0104	37.80	5.858	1.961	9.802	0.925	0.310	1.100	0.053	0.018
320/DAA/114	46.0	429.0	3.7	0.0075	12.38	2.667	0.893	55.73	7.309	2.447	2.100	0.141	0.047
321/DAA/114	46.0	425.0	4.4	0.0067	5.80	1.382	0.463	104.0	15.08	5.049	6.00	0.446	0.149
322/DAA/114	46.0	422.0	4.8	0.0064	4.00	0.999	0.334	175.9	26.74	8.950	11.50	0.896	0.300
323/DAA/111	53.0	458.0	3.5	0.0104	35.36	5.475	1.833	10.79	1.018	0.341	1.200	0.058	0.019
324/DAA/111	46.0	424.0	3.7	0.0074	13.36	2.893	0.969	18.75	2.472	0.828	1.200	0.081	0.027
325/DAA/115	53.0	457.0	3.4	0.0104	33.06	5.148	1.723	7.84	0.743	0.249	1.50	0.073	0.024
326/DAA/115	46.0	425.0	3.6	0.0074	12.54	2.730	0.914	68.06	9.022	3.020	2.70	0.184	0.061

TABLE B-2 (cont.)

Test No./ Fuel Nozzle/ Combustor Mod	Inlet Air Pressure	Inlet Air Temp.	Combustor Pressure Loss	Fuel-Air Ratio	Pollutant Emissions								
					NO$_x$ (NO$_2$)			CO			UHC (C$_6$H$_{14}$)		
	psig	F	$\frac{\text{Pin - Pout}}{\text{Pin}}$ x100		ppm	EI	g/mi*	ppm	EI	g/mi*	ppm C	EI	g/mi*
327/DAA/116	53.0	460.0	3.5	0.0103	34.30	5.362	1.795	8.82	0.839	0.281	1.10	0.054	0.018
328/DAA/116	46.0	430.0	3.6	0.0075	13.12	2.826	0.946	45.86	6.014	2.013	1.80	0.121	0.041
329/DAA/117	53.0	460.0	3.3	0.0104	35.04	5.436	1.820	5.86	0.556	0.186	0.70	0.034	0.011
330/DAA/117	46.0	425.0	3.5	0.0074	14.34	3.110	1.041	48.31	6.379	2.135	1.40	0.095	0.032
331/DAA/117	46.0	425.0	4.2	0.0067	7.80	1.878	0.629	170.4	24.98	8.363	6.00	0.451	0.151
332/DAA/118	53.0	460.0	4.8	0.0103	27.50	4.299	1.439	7.83	0.745	0.250	1.00	0.049	0.016
333/DAA/118	46.0	425.0	4.9	0.0074	3.48	0.761	0.255	492.8	65.60	21.96	30.10	2.055	0.688
334/DAA/118	46.0	425.0	4.5	0.0078	6.70	1.390	0.465	341.5	43.14	14.44	10.17	0.659	0.221
335/DAA/119	53.0	460.0	4.6	0.0104	28.36	4.408	1.476	11.75	1.112	0.372	2.00	0.097	0.032
336/DAA/119	46.0	425.0	4.7	0.0074	2.67	0.581	0.194	492.8	65.25	21.84	48.00	3.259	1.091
337/DAA/120	53.0	457.0	4.9	0.0103	25.86	4.035	1.351	7.337	0.697	0.233	1.600	0.078	0.026
338/DAA/120	46.0	425.0	5.1	0.0074	4.340	0.944	0.3160	421.3	55.79	18.68	18.30	1.243	0.416
339/DAA/121	53.0	455.0	4.9	0.0104	25.16	3.911	1.309	9.30	0.880	0.295	1.20	0.058	0.019
340/DAA/121	46.0	426.0	5.1	0.0074	4.16	0.908	0.304	445.6	59.24	19.83	22.30	1.520	0.509

TABLE B-2 (cont.)

Test No./ Fuel Nozzle/ Combustor Mod	Inlet Air Pressure	Inlet Air Temp.	Combustor Pressure Loss	Fuel-Air Ratio	Pollutant Emissions								
					NO_x (NO_2)			CO			UHC (C_6H_{14})		
	psig	F	$\frac{Pin - Pout}{Pin}$ x100		ppm	EI	g/mi*	ppm	EI	g/mi*	ppm C	EI	g/mi*
341/DAA/122	53.0	460.0	4.8	0.0105	26.60	4.088	1.368	9.298	0.870	0.291	4.400	0.211	0.071
342/DAA/122	46.0	425.0	5.0	0.0073	6.32	1.386	0.464	465.9	62.19	20.82	46.90	3.210	1.075
349/DAA/122	53.0	458.0	4.9	0.0104	28.26	4.388	1.469	9.363	0.885	0.296	0.900	0.044	0.015
350/DAA/122	46.0	421.0	5.0	0.0074	5.22	1.137	0.381	493.6	65.45	21.91	49.10	3.338	1.118
351/DAA/120	53.0	459.0	4.9	0.0104	26.00	4.033	1.350	8.33	0.787	0.263	1.40	0.068	0.023
352/DAA/120	46.0	425.0	5.1	0.0073	4.94	1.086	0.364	470.5	62.98	21.08	30.90	2.121	0.710
353/DAA/123	53.0	460.0	4.3	0.0103	23.90	3.733	1.250	2.450	0.233	0.078	4.300	0.210	0.070
354/DAA/123	46.0	425.0	4.4	0.0074	10.32	2.256	0.755	32.06	4.268	1.429	2.00	0.137	0.046
355/DAA/124	53.0	460.0	4.3	0.0104	23.72	3.683	1.233	2.450	0.232	0.078	2.800	0.136	0.045
356/DAA/124	46.0	420.0	4.4	0.0074	10.02	2.173	0.727	47.37	6.254	2.094	1.200	0.081	0.027
357/DAA/125	53.0	460.0	4.2	0.0104	25.16	3.914	1.310	3.920	0.371	0.124	1.500	0.073	0.024
358/DAA/125	46.0	425.0	4.3	0.0074	11.00	2.405	0.805	86.34	11.49	3.847	1.700	0.116	0.039
359/DAA/126	53.0	463.0	3.6	0.0104	25.62	3.982	1.333	6.370	0.603	0.202	2.300	0.112	0.037
360/DAA/126	46.0	425.0	3.7	0.0073	6.680	1.465	0.490	361.5	48.26	16.16	11.20	0.767	0.257

TABLE B-2 (cont.)

Test No./ Fuel Nozzle/ Combustor Mod	Inlet Air Pressure	Inlet Air Temp.	Combustor Pressure Loss	Fuel-Air Ratio	Pollutant Emissions								
					NO_x (NO_2)			CO			UHC (C_6 H_{14})		
	psig	F	$\frac{Pin - Pout}{Pin}$ x100		ppm	EI	g/mi*	ppm	EI	g/mi*	ppm C	EI	g/mi*
414/AB/12	46.0	425.0	4.3	0.0067	15.00	3.606	1.207	10.85	1.588	0.532	3.14	0.236	0.079
415/AB/123	46.0	425.0	4.3	0.0067	13.90	3.351	1.122	15.79	2.318	0.776	4.26	0.321	0.107
416/AB/123	46.0	425.0	4.3	0.0071	15.38	3.465	1.160	7.89	1.082	0.362	5.14	0.362	0.121
417/AB/123	53.0	460.0	4.2	0.0092	24.46	4.271	1.430	3.93	0.417	0.140	4.42	0.241	0.081
418/AB/123	53.0	460.0	4.3	0.0103	29.64	4.647	1.556	7.83	0.748	0.250	4.64	0.227	0.076
419/AB/126	46.0	425.0	3.7	0.0067	7.70	1.849	0.619	338.3	49.45	16.55	14.04	1.052	0.352
420/AB/126	46.0	425.0	3.7	0.0072	12.16	2.732	0.915	175.9	24.06	8.055	3.84	0.269	0.090
421/AB/126	53.0	460.0	3.6	0.0092	25.42	4.429	1.483	4.41	0.468	0.157	2.60	0.141	0.047
422/AB/126	53.0	460.0	3.7	0.0103	28.08	4.390	1.470	2.93	0.279	0.093	2.44	0.119	0.040
423/DAA/127	46.0	425.0	3.6	0.0071	9.18	2.066	0.692	307.4	42.11	14.10	6.96	0.489	0.164
424/DAA/127	53.0	450.0	3.5	0.0103	27.34	4.282	1.434	9.77	0.932	0.312	8.90	0.435	0.146
425/DAA/128	46.0	425.0	3.5	0.0072	5.30	1.189	0.398	492.8	67.33	22.54	26.70	1.871	0.626
426/DAA/128	53.0	460.0	3.4	0.0103	24.90	3.889	1.302	5.38	0.511	0.171	1.68	0.082	0.027
427/DAA/129	46.0	425.0	3.9	0.0072	7.92	1.780	0.596	192.0	26.27	8.796	5.04	0.354	0.118
428/DAA/129	53.0	460.0	3.9	0.0103	23.34	3.645	1.220	4.89	0.465	0.156	1.56	0.076	0.025

TABLE B-2 (cont.)

Test No./ Fuel Nozzle/ Combustor Mod	Inlet Air Pressure	Inlet Air Temp.	Combustor Pressure Loss	Fuel-Air Ratio	Pollutant Emissions								
					NO_x (NO_2)			CO			UHC (C_6H_{14})		
	psig	F	$\frac{\text{Pin - Pout}}{\text{Pin}}$ x100		ppm	EI	g/mi*	ppm	EI	g/mi*	ppm C	EI	g/mi*
429/DAA/130	46.0	425.0	3.8	0.0072	7.20	1.618	0.542	287.1	39.29	13.15	11.02	0.773	0.259
430/DAA/130	53.0	460.0	3.8	0.0103	24.34	3.809	1.275	4.88	0.465	0.156	1.32	0.064	0.022
432/AB/132	46.0	423.0	6.1	0.0072	3.16	0.709	0.237	495.3	67.62	22.64	1905.0	133.4	44.65
433/AB/132	53.0	460.0	6.5	0.0103	6.30	0.983	0.329	490.5	46.60	15.60	460.0	22.41	7.501
434/AB/133	46.0	425.0	7.8	0.0072	2.94	0.658	0.220	495.4	67.53	22.61	2170.0	151.7	50.78
435/AB/133	53.0	460.0	8.1	0.0103	6.72	1.056	0.353	489.4	46.82	15.67	90.40	4.434	1.484
436/AB/134	46.0	425.0	6.4	0.0072	3.60	0.808	0.270	494.6	67.55	22.61	1020.0	71.43	23.91
437/AB/134	53.0	460.0	7.1	0.0103	10.50	1.640	0.549	23.95	2.278	0.762	14.60	0.712	0.238
438/AB/135	46.0	425.0	5.2	0.0071	3.96	0.891	0.298	493.7	67.63	22.64	352.0	24.73	8.278
439/AB/135	53.0	460.0	5.3	0.0103	15.76	2.464	0.825	7.82	0.745	0.249	3.50	0.171	0.057
440/AB/136	46.0	425.0	4.9	0.0072	3.72	0.833	0.279	494.7	67.47	22.59	870.0	60.85	20.37
441/AB/136	53.0	460.0	4.9	0.0103	12.48	1.951	0.653	43.05	4.097	1.372	4.20	0.205	0.069
442/AB/137	46.0	425.0	3.7	0.0071	3.80	0.855	0.286	493.6	67.63	22.64	203.0	14.26	4.774
443/AB/137	53.0	460.0	3.8	0.0103	20.0	3.13	1.048	5.87	0.559	0.187	2.30	0.112	0.038

TABLE B-2 (cont.)

Test No./ Fuel Nozzle/ Combustor Mod	Inlet Air Pressure	Inlet Air Temp.	Combustor Pressure Loss	Fuel-Air Ratio	Pollutant Emissions								
					NO_x (NO_2)			CO			UHC (C_6H_{14})		
	psig	F	$\frac{\text{Pin - Pout}}{\text{Pin}}$ x100		ppm	EI	g/mi*	ppm	EI	g/mi*	ppm C	EI	g/mi*
444/AB/138	46.0	425.0	2.9	0.0072	7.82	1.757	0.588	140.0	19.16	6.414	11.20	0.786	0.263
445/AB/138	53.0	460.0	2.9	0.0103	24.36	3.815	1.277	13.22	1.260	0.422	2.20	0.108	0.036
446/AB/139	46.0	425.0	2.5	0.0072	7.96	1.784	0.597	135.1	18.43	6.169	8.70	0.609	0.204
447/AB/139	53.0	460.0	2.7	0.0103	24.64	3.859	1.292	10.76	1.026	0.344	1.90	0.093	0.031
448/AB/140	46.0	425.0	2.8	0.0071	6.74	1.517	0.508	193.7	26.54	8.885	15.80	1.110	0.372
449/AB/140	53.0	460.0	2.8	0.0103	22.10	3.458	1.158	11.74	1.118	0.374	0.5	0.024	0.008
450/AB/141	46.0	425.0	2.7	0.0070	6.08	1.401	0.469	288.5	40.48	13.55	42.90	3.087	1.033
451/AB/141	53.0	460.0	2.8	0.0101	23.86	3.796	1.271	10.28	0.995	0.333	1.68	0.083	0.028
452/AB/140	46.0	425.0	2.8	0.0070	6.46	1.489	0.498	253.4	35.56	11.90	41.36	2.976	0.996
453/AB/140	53.0	458.0	2.8	0.0101	21.40	3.404	1.140	9.32	0.902	0.302	0.55	0.027	0.009
454/AB/140	46.0	425.0	2.8	0.0071	6.80	1.537	0.514	173.5	23.87	7.991	18.30	1.291	0.432
455/AB/140	53.0	460.0	2.8	0.0104	24.50	3.783	1.266	14.66	1.379	0.462	3.40	0.164	0.055
456/AB/141	46.0	425.0	2.7	0.0071	[illegible]	1.131	0.379	321.4	44.10	14.76	64.80	4.559	1.526
457/AB/141	53.0	460.0	2.7	0.0105	22.12	3.412	1.142	13.70	1.286	0.431	1.16	0.056	0.019

TABLE B-2 (cont.)

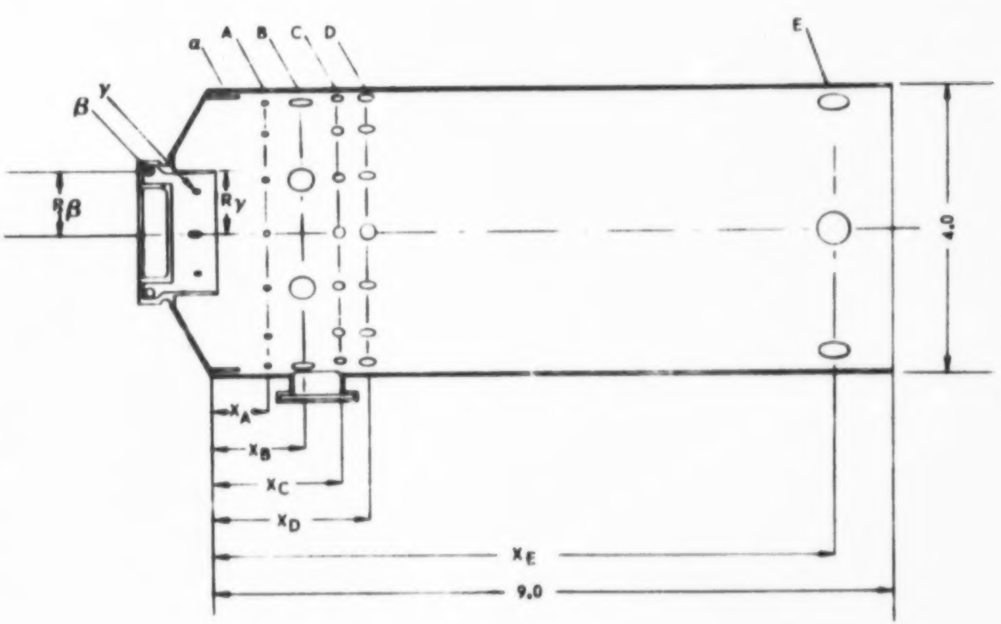
Test No./ Fuel Nozzle/ Combustor Mod	Inlet Air Pressure	Inlet Air Temp.	Combustor Pressure Loss	Fuel-Air Ratio	Pollutant Emissions								
					NO_x (NO_2)			CO			UHC (C_6H_{14})		
	psig	F	$\frac{P_{in} - P_{out}}{P_{in}} \times 100$		ppm	EI	g/mi*	ppm	EI	g/mi*	ppm C	EI	g/mi*
458/AB/142	46.0	425.0	2.9	0.0074	8.28	1.793	0.600	18.72	2.469	0.826	2.24	0.151	0.051
459/AB/142	53.0	460.0	2.9	0.0107	27.2	4.118	1.379	31.27	2.882	0.965	2.14	0.101	0.034
460/AB/143	46.0	425.0	3.1	0.0073	6.70	1.475	0.494	40.42	5.417	1.813	2.44	0.168	0.056
461/AB/143	53.0	460.0	3.2	0.0104	30.50	4.741	1.587	25.46	2.409	0.807	3.66	0.178	0.059
462/AB/144	46.0	425.0	3.6	0.0074	4.34	0.949	0.318	283.9	37.80	12.65	28.50	1.945	0.651
463/AB/144	53.0	460.0	3.6	0.0104	19.64	3.050	1.021	9.30	0.879	0.294	1.24	0.060	0.020
464/AB/145	46.0	425.0	3.3	0.0074	6.22	1.354	0.453	75.90	10.06	3.368	4.50	0.306	0.102
465/AB/145	53.0	460.0	3.4	0.0104	25.60	3.971	1.330	17.13	1.618	0.542	1.86	0.090	0.030
466/AB/146	46.0	425.0	3.2	0.00735	6.80	1.487	0.498	60.12	8.003	2.679	3.46	0.236	0.079
467/AB/146	53.0	460.0	3.4	0.01040	25.18	3.899	1.305	18.61	1.754	0.587	2.88	0.139	0.047
468/AB/145	46.0	425.0	3.3	0.00733	5.72	1.254	0.420	136.5	18.22	6.10	8.32	0.569	0.191
469/AB/145	53.0	460.0	3.5	0.01036	22.86	3.557	1.191	12.24	1.159	0.388	2.10	0.102	0.034
470/AB/147	46.0	425.0	3.3	0.00735	6.12	1.338	0.448	108.4	14.43	4.832	5.52	0.377	0.126
471/AB/147	53.0	460.0	3.4	0.01038	23.02	3.575	1.197	13.21	1.249	0.418	1.88	0.091	0.031
472/AB/147	53.0	460.0	3.1	0.00519	2.46	0.760	0.254	800*	151*	50.5*	574.4	55.39	18.54
474/AB/147	46.0	425.0	3.5	0.01502	66.20	7.138	2.390	185.4	12.17	4.074	1.14	0.038	0.013

TABLE B-2 (cont.)

Test No./ Fuel Nozzle/ Combustor Mod	Inlet Air Pressure	Inlet Air Temp.	Combustor Pressure Loss	Fuel-Air Ratio	Pollutant Emissions								
					NO_x (NO_2)			CO			UHC (C_6H_{14})		
	psig	F	$\frac{Pin - Pout}{Pin}$ x100		ppm	EI	g/mi*	ppm	EI	g/mi*	ppm C	EI	g/mi*
475/AB/148	46.0	425.0	3.3	.00725	7.1	1.57	.527	74.9	10.11	3.38	3.1	0.21	.072
476/AB/148	53.0	460.0	3.4	.01036	24.8	3.86	1.29	13.7	1.30	0.434	1.18	0.057	.019
477/AB/148	53.0	460.0	3.1	.00518	2.84	.879	.294	496	93.5	31.3	446	43.1	14.43
478/AB/148	46.0	425.0	3.3	.01506	68.4	7.36	2.46	189	12.4	4.15	1.16	.0389	.013
479/AB/148	37.0	460.0	3.2	.0104	15.9	2.46	.825	14.2	1.34	.447	2.3	.112	.0375
480/AB/148	53.0	590.0		.00848	14.7	2.79	.935	3.44	.397	.133	2.3	.136	.0456
481/AB/148	69.0	530.0	3.2	.0139	85.6	9.96	3.33	74.7	5.29	1.77	0.24	.009	.003
483/AB/148	60.0	490.0	3.2	.01255	55.2	7.10	2.38	47.7	3.74	1.25	2.60	.105	.035
484/AB/148	53.0	590.0	3.2	.01038	36.7	5.70	1.91	11.8	1.11	.372	1.84	.089	.0299
485/AB/148	69.0	420.0	3.3	.0142	57.2	6.53	2.18	88.7	6.16	2.06	0.88	.031	.010
486/AB/148	55.0	530.0	3.5	.0140	81.6	9.39	3.14	89.3	6.25	2.09	0.54	.019	.006
487/AB/148	80.0	530.0	3.0	.0139	91.3	10.62	3.55	71.9	5.09	1.71	0.43	0.016	.005
488/AB/148	83.0	585.0	2.9	.0157	153.6	15.82	5.30	141.7	8.89	2.98	0.30	.010	.003
489/AB/148	100.0	530.0	2.8	.0140	109.0	12.52	4.19	50.44	3.53	1.18	0.50	0.018	.006
490/AB/148	97.0	630.0	3.0	.0169	207.5	19.91	6.67	109.5	6.40	2.14	00	00	00
491/AB/148	129.0	530.0	2.4	.0152	155.3	16.55	5.54	37.96	2.47	0.83	4.25	0.142	.047

TABLE B-3

SUMMARY OF REGENERATIVE-CYCLE (CLASS A/MOD) COMBUSTOR CONFIGURATIONS



MOD	A			B			C			D			E			α			β			γ			AIR SWIRLER
	Dia.	No	X_A	Dia.	No	X_B	Dia.	No	X_C	Dia.	No	X_D	Dia.	No	X_E	Dia.	No	R_α	Dia.	No	R_β	Dia.	No	R_γ	
1	.062	16	.95	.300	8	1.5	.150	16	1.87	.200	16	.219	.441	6	8.2	.120	40	4.0	.166	10	.95	.125	8	.88	—
2	.125	16	.95	.300	8	1.5	.213	16	1.87	.200	16	.219	.441	6	8.2	.120	40	4.0	.166	10	.95	.125	8	.88	—
3	.166	16	.95	.300	8	1.5	.213	16	1.87	.200	16	.219	.441	6	8.2	.120	40	4.0	.166	10	.95	.125	8	.88	—
4	.166	16	.95	.300	8	1.5	.213	16	1.87	.250	16	.219	.312	6	8.2	.120	40	4.0	.166	10	.95	.125	8	.88	—
5	.166	16	.95	.300	8	1.5	.213	16	1.87	.250	16	.219	—	—	—	.120	40	4.0	.166	10	.95	.125	8	.88	—

TABLE B-3 (cont.)

A			B			C			D			E			α			β			γ			AIR SWIRLER
Dia.	No	X_A	Dia.	No	X_B	Dia.	No	X_C	Dia.	No	X_D	Dia.	No	X_E	Dia.	No	Rα	Dia.	No	Rβ	Dia.	No	Rγ	
.166	16	.95	.300	8	1.5	.151	16	1.87	—	—	—	.441	6	8.2	.120	40	4.0	.166	10	.95	.125	8	.88	—
.166	31	.95	.300	8	1.5	.151	16	1.87	—	—	—	.441	6	8.2	.120	40	4.0	.166	10	.95	.125	8	.88	—
.166	31	.95	.300	8	1.5	—	—	—	—	—	—	.441 .228	6 6	8.2 8.2	.120	40	4.0	.166	10	.95	.125	8	.88	—
.170	31	.95	.300	8	1.5	.151	16	1.87	—	—	—	.441	6	8.2	.120	40	4.0	.166	10	.95	.125	8	.88	—
.170	31	.95	.300	8	1.5	.151	16	1.87	—	—	—	.441	6	8.2	.120	36	4.0	.166	10	.95	.125	8	.88	—
.170	31	.95	.300	8	1.5	.151	16	1.87	—	—	—	.418	6	8.2	.120	36	4.0	.166	10	.95	.125	8	.88	—
.160	31	.70	.209	16	1.5	.151	16	1.87	—	—	—	.418	6	8.2	.120	36	4.0	.166	10	.95	.125	8	.88	—
.160	31	.70	.300	8	1.5	.151	16	1.87	—	—	—	.418	6	8.2	.120	36	4.0	.166	10	.95	.125	8	.88	—
.160	31	.70	.300 .209	8 16	1.5 1.5	.151	16	1.87	—	—	—	.242	6	8.2	.120	36	4.0	.166	10	.95	.125	8	.88	—
.160	31	.70	.300	15	1.5	.151	16	1.87	—	—	—	.242	6	8.2	.120	36	4.0	.166	10	.95	.125	8	.88	—
.160	31	.70	.300 Plunged 3/16	8	1.5	.151	16	1.87	—	—	—	.418	6	8.2	.120	36	4.0	.166	10	.95	.125	8	.88	—
.160	31	.70	.300 Plunged 3/16	8	1.5	—	—	—	—	—	—	.418	6	8.2	.120	36	4.0	.166	10	.95	.125	8	.88	—
.160	31	.70	.260	8	1.5	—	—	—	—	—	—	.418	6	8.2	.120	36	4.0	.166	10	.95	.125	8	.88	—
.160	31	.70	.260	8	1.5	—	—	—	—	—	—	.418	6	8.2	.120	36	4.0	.166	10	.95	.125	8	.88	4
.160	31	.70	.150	8	1.5	—	—	—	—	—	—	.441 .218	6 6	8.2 8.2	.120	36	4.0	.166	10	.95	.125	8	.88	4

TABLE B-3 (cont.)

MOD	A			B			C			D			E			α			β			γ			AIR SWIRLER
	Dia.	No	X_A	Dia.	No	X_B	Dia.	No	X_C	Dia.	No	X_D	Dia.	No	X_E'	Dia.	No	R_α	Dia.	No	R_β	Dia.	No	R_γ	
21	.160	31	.70	—	—	—	—	—	—	.172	6	7.7	.441 .218	6 6	8.2 8.2	.120	36	4.0	.166	10	.95	.125	8	.88	4
22	.160	31	.70	—	—	—	—	—	—	.172	6	7.7	.441 .218	6 6	8.2 8.2	.120	36	4.0	.166	10	.95	.125	8	.88	5
23	.113	31	.70	—	—	—	—	—	—	.172 .262	6 6	7.7 7.7	.441 .218	6 6	8.2 8.2	.120	36	4.0	.166	10	.95	.125	8	.88	5
24	.138	31	.70	—	—	—	—	—	—	.172 .272	6 6	7.7 7.7	.441 .218	6 6	8.2 8.2	.120	36	4.0	.166	10	.95	.125	8	.88	5
25	.127	31	.70	—	—	—	—	—	—	.172 .272	6 6	7.7 7.7	.441 .218	6 6	8.2 8.2	.120	36	4.0	.166	10	.95	.125	8	.88	5
26	.113	31	.70	—	—	—	—	—	—	.172 .272 .080	6 6 6	7.7 7.7 7.7	.441 .218	6 6	8.2 8.2	.120	36	4.0	.166	10	.95	.125	8	.88	5

TABLE B-4

SUMMARY OF TEST DATA FROM REGENERATIVE-CYCLE (CLASS A/MOD) COMBUSTOR (ZERO HUMIDITY)

Test No./ Fuel Nozzle/ Combustor Mod	Inlet Air Pressure	Inlet Air Temp.	Combustor Pressure Loss	Fuel-Air Ratio	Pollutant Emissions								
					NO_x (NO_2)			CO			UHC (C_6H_{14})		
	psig	F	$\frac{Pin - Pout}{Pin}$ x100		ppm	EI	g/mi*	ppm	EI	g/mi*	ppm C	EI	g/mi*
361/AB/0	13.0	995.0	7.4	0.0115	18.50	2.598	0.589	65.12	5.568	1.262	3.50	0.153	0.035
362/AB/0	13.0	1000.0	7.5	0.0115	31.40	4.410	1.000	62.53	5.347	1.212	1.00	0.044	0.010
363/AB/0	13.0	1000.0	7.4	0.0062	12.50	3.221	0.730	259.7	40.74	9.235	50.00	4.022	0.912
364/AB/1	13.0	1000.0	8.7	0.0062	15.24	3.926	0.890	86.47	13.56	3.075	0.80	0.064	0.015
365/AB/2	13.0	1000.0	6.1	0.0062	14.18	3.665	0.831	163.1	25.66	5.818	8.10	0.654	0.148
366/AB/2	13.0	977.0	6.0	0.0051	10.26	3.244	0.736	190.2	36.62	8.301	7.30	0.721	0.163
367/AB/2	13.0	1075.0	6.1	0.0070	20.96	4.824	1.093	98.65	13.82	3.133	4.60	0.331	0.075
368/AB/3	13.0	1000.0	5.5	0.0063	15.10	3.872	0.878	165.5	25.84	5.858	2.40	0.192	0.044
369/AB/3	13.0	995.0	5.6	0.0063	14.35	3.676	0.833	170.0	26.45	5.997	9.40	0.750	0.170
370/AB/3	13.0	977.0	5.5	0.0051	10.74	3.363	0.762	189.2	36.07	8.177	5.10	0.499	0.113
371/AB/4	13.0	1000.0	6.1	0.0062	14.05	3.626	0.822	204.6	32.14	7.286	13.20	1.063	0.241
372/AB/4	13.0	980.0	6.0	0.0051	10.18	3.232	0.733	210.0	40.58	9.200	12.50	1.239	0.281
373/AB/4	13.0	996.0	6.0	0.0062	14.06	3.640	0.825	204.5	32.23	7.306	9.90	0.800	0.181
374/AB/5	13.0	980.0	7.8	0.0051	10.50	3.320	0.753	252.5	48.62	11.02	18.40	1.816	0.412
375/AB/5	13.0	1000.0	7.9	0.0062	14.04	3.623	0.821	249.0	39.11	8.867	12.50	1.007	0.228

* Vehicle Fuel Economy = 12.7 miles/gal

TABLE B-4 (cont.)

Test No./ Fuel Nozzle/ Combustor Mod	Inlet Air Pressure	Inlet Air Temp.	Combustor Pressure Loss	Fuel-Air Ratio	Pollutant Emissions								
					NO_x (NO_2)			CO			UHC (C_6H_{14})		
	psig	F	$\frac{Pin - Pout}{Pin}$ x100		ppm	EI	g/mi*	ppm	EI	g/mi*	ppm C	EI	g/mi*
376/AB/6	13.0	983.0	8.5	0.0051	9.08	2.883	0.654	224.3	43.36	9.829	5.85	0.580	0.131
377/AB/6	13.0	1000.0	8.8	0.0062	12.70	3.288	0.745	170.0	26.79	6.073	4.00	0.323	0.073
378/AB/7	13.0	980.0	6.7	0.0050	6.880	2.189	0.496	334.8	64.84	14.70	4.90	0.487	0.110
379/AB/7	13.0	1000.0	6.9	0.0062	10.54	2.733	0.620	283.1	44.69	10.13	2.50	0.202	0.046
380/AB/7	13.0	1073.0	7.2	0.0070	15.42	3.554	0.806	162.3	22.77	5.161	2.12	0.153	0.035
381/AB/8	13.0	985.0	6.7	0.0051	10.82	3.422	0.776	194.1	37.37	8.471	3.08	0.304	0.069
382/AB/8	13.0	1000.0	6.8	0.0062	14.90	3.833	0.869	155.1	24.28	5.505	2.30	0.185	0.042
383/AB/9	13.0	1000.0	6.5	0.0062	12.58	3.241	0.735	266.7	41.84	9.484	5.94	0.478	0.108
384/AB/10	13.0	980.0	6.5	0.0052	8.46	2.614	0.593	329.5	61.99	14.05	4.80	0.463	0.105
385/AB/10	13.0	980.0	6.5	0.0050	7.18	2.289	0.519	337.7	65.54	14.86	4.48	0.446	0.101
386/AB/10	13.0	1000.0	6.7	0.0062	11.30	2.935	0.665	280.5	44.36	10.06	1.38	0.112	0.025
387/AB/10	13.0	1083.0	7.1	0.0070	16.50	3.814	0.865	156.7	22.06	5.00	0.58	0.042	0.009
389/AB/11	13.0	980.0	7.0	0.0050	7.04	2.253	0.511	364.5	71.01	16.10	4.98	0.498	0.113
390/AB/11	13.0	1000.0	7.0	0.0062	10.82	2.792	0.633	297.8	46.79	10.61	1.40	0.113	0.026
391/AB/11	13.0	1072.0	7.4	0.0069	15.14	3.504	0.794	177.4	25.01	5.669	0.70	0.051	0.011

TABLE B-4 (cont.)

Test No./ Fuel Nozzle/ Combustor Mod	Inlet Air Pressure	Inlet Air Temp.	Combustor Pressure Loss	Fuel-Air Ratio	Pollutant Emissions								
					NO_x (NO_2)			CO			UHC (C_6H_{14})		
	psig	F	$\frac{Pin - Pout}{Pin}$ x100		ppm	EI	g/mi*	ppm	EI	g/mi*	ppm C	EI	g/mi*
405/AB/12	13.0	980.0	7.2	0.0051	8.92	2.810	0.637	277.4	53.19	12.06	2.06	0.203	0.046
406/AB/12	13.0	1000.0	7.2	0.0063	13.10	3.349	0.759	269.8	41.99	9.518	1.18	0.094	0.021
407/AB/13	13.0	977.0	7.2	0.0049	7.18	2.339	0.530	310.1	61.52	13.95	3.22	0.328	0.074
408/AB/13	13.0	1000.0	7.2	0.0062	10.42	2.689	0.610	290.6	45.65	10.35	1.42	0.114	0.026
409/AB/13	13.0	1090.0	7.8	0.0070	15.04	3.476	0.788	168.7	23.74	5.38	0.70	0.051	0.011
410/AB/14	13.0	980.0	7.1	0.0051	8.12	2.563	0.581	340.7	65.48	14.84	3.70	0.365	0.083
411/AB/14	13.0	1000.0	7.2	0.0062	11.06	2.845	0.645	386.4	60.52	13.72	2.34	0.188	0.043
412/AB/15	13.0	980.0	7.5	0.0051	8.04	2.553	0.579	336.7	65.09	14.75	2.48	0.246	0.056
413/AB/15	13.0	1000.0	7.6	0.0062	11.26	2.906	0.659	352.7	55.42	12.56	1.36	0.110	0.025

TABLE B-4 (cont.)

Test No./ Fuel Nozzle/ Combustor Mod	Inlet Air Pressure	Inlet Air Temp.	Combustor Pressure Loss	Fuel-Air Ratio	Pollutant Emissions								
					NO$_x$ (NO$_2$)			CO			UHC (C_6H_{14})		
	psig	F	$\frac{\text{Pin - Pout}}{\text{Pin}}$ x100		ppm	EI	g/mi*	ppm	EI	g/mi*	ppm C	EI	g/mi*
492/AB/16	13.0	980.0	6.1	0.00502	8.60	2.747	0.623	263.6	51.25	11.62	8.20	0.818	0.185
493/AB/16	13.0	1000.0	6.1	0.00633	13.06	3.312	0.751	258.4	39.89	9.043	4.60	0.364	0.083
494/AB/16	13.0	980.0	6.3	0.00502	9.10	2.906	0.659	265.0	51.53	11.68	6.00	0.598	0.136
495/AB/16	13.0	1000.0	6.4	0.00621	12.78	3.303	0.749	268.8	42.30	9.589	3.70	0.299	0.068
496/AB/17	13.0	1000.0	7.9	0.00617	13.10	3.408	0.773	244.5	38.73	8.780	2.10	0.171	0.039
497/AB/18	13.0	980.0	9.7	0.00507	8.34	2.637	0.598	279.5	53.81	12.20	2.10	0.207	0.047
498/AB/18	13.0	1000.0	9.9	0.00627	11.68	2.990	0.678	261.9	40.82	9.253	1.40	0.112	0.025
499/AB/18	13.0	1100.0	11.1	0.00691	14.76	3.431	0.778	195.8	27.72	6.283	2.90	0.211	0.048
500/AB/19	13.0	1000.0	9.4	0.00626	9.44	2.421	0.549	295.6	46.15	10.46	22.20	1.777	0.403
501/AB/19	13.0	1100.0	10.0	0.00691	13.82	3.212	0.728	157.9	22.35	5.067	15.70	1.139	0.258
502/AB/20	13.0	1000.0	8.8	0.00627	10.70	2.739	0.621	181.2	28.25	6.404	3.80	0.304	0.069
503/AB/20	13.0	980.0	8.8	0.00508	5.42	1.711	0.388	378.3	72.70	16.48	5.30	0.522	0.118
504/AB/20	13.0	1100.0	9.4	0.00696	14.52	3.351	0.760	86.79	12.20	2.765	3.10	0.223	0.056
505/AB/21	13.0	980.0	8.7	0.00503	6.62	2.110	0.478	301.0	58.41	13.24	2.90	0.289	0.065
506/AB/21	13.0	1000.0	8.7	0.00626	11.34	2.908	0.659	127.4	19.89	4.509	1.60	0.128	0.029
507/AB/21	13.0	1100.0	9.5	0.00690	16.16	3.762	0.853	61.65	8.737	1.981	1.90	0.138	0.031

TABLE B-4 (cont.)

Test No./ Fuel Nozzle/ Combustor Mod	Inlet Air Pressure	Inlet Air Temp.	Combustor Pressure Loss	Fuel-Air Ratio	Pollutant Emissions								
					NO_x (NO_2)			CO			UHC (C_6H_{14})		
	psig	F	$\frac{Pin - Pout}{Pin}$ x100		ppm	EI	g/mi*	ppm	EI	g/mi*	ppm C	EI	g/mi*
508/AB/22	13.0	980.0	7.4	0.00505	2.400	0.762	0.173	495.5	95.78	21.71	88.20	8.742	1.982
509/AB/22	13.0	1000.0	7.9	0.00623	8.34	2.149	0.487	375.3	58.88	13.35	2.10	0.169	0.038
510/AB/22	13.0	1100.0	8.4	0.00685	14.36	3.367	0.763	98.63	14.08	3.192	0.70	0.051	0.012
511/AB/23	13.0	1000.0	8.1	0.00627	8.58	2.196	0.498	81.01	12.63	2.862	4.40	0.352	0.080
512/AB/23	13.0	1100.0	8.6	0.00692	13.78	3.198	0.725	21.21	2.997	0.679	2.70	0.196	0.044
513/AB/24	13.0	980.0	6.7	0.00508	4.26	1.345	0.305	457.5	87.92	19.93	15.30	1.508	0.342
514/AB/24	13.0	1000.0	6.9	0.00629	9.96	2.542	0.576	92.84	14.42	3.27	1.20	0.096	0.022
515/AB/24	13.0	1100.0	7.5	0.00692	14.92	3.463	0.785	26.62	3.762	0.853	1.80	0.130	0.030
516/AB/25	13.0	980.0	6.9	0.00509	4.20	1.323	0.300	441.8	84.74	19.21	29.30	2.882	0.653
517/AB/25	13.0	1000.0	7.0	0.00628	10.56	2.699	0.612	106.2	16.53	3.747	2.30	0.184	0.042
518/AB/25	13.0	1100.0	7.4	0.00691	16.06	3.733	0.846	31.08	4.398	0.997	1.90	0.138	0.031
519/AB/26	13.0	1000.0	6.9	0.00627	11.08	2.836	0.643	64.23	10.01	2.269	0.30	0.024	0.005
520/AB/26	13.0	1100.0	7.5	0.00687	18.88	4.414	1.001	15.78	2.247	0.509	0.20	0.015	0.003
521/AB/26	13.0	980.0	6.7	0.00526	6.18	1.884	0.427	286.1	53.11	12.04	2.60	0.248	0.056

TABLE B-4 (cont.)

Test No./ Fuel Nozzle/ Combustor Mod	Inlet Air Pressure	Inlet Air Temp.	Combustor Pressure Loss	Fuel-Air Ratio	Pollutant Emissions								
					NO_x (NO_2)			CO			UHC (C_6H_{14})		
	psig	F	$\frac{Pin - Pout}{Pin}$ x100		ppm	EI	g/mi*	ppm	EI	g/mi*	ppm C	EI	g/mi*
522/AB/23	13.0	1000.0	7.7	0.00627	9.88	2.529	0.573	96.31	15.01	3.403	—	—	—
523/AB/23	13.0	1100.0	8.3	0.00691	15.50	3.603	0.817	22.69	3.211	0.728	0.10	0.007	0.002
524/AB/23	13.0	980.0	7.6	0.00545	5.60	1.648	0.374	354.8	63.57	14.41	7.70	0.708	0.160
526/AB/23	25.0	1120.0	11.7	0.0075	21.8	4.671	1.059	11.32	1.477	0.335	0.30	0.020	0.0045
527/AB/23	40.0	960.0	—	0.0105	36.1	5.553	1.259	6.36	0.595	0.135	—	—	—
528/AB/23	59.0	1100.0	—	0.0109	49.2	7.312	1.658	4.894	0.443	0.100	—	—	—
529/AB/23	59.0	1100.0	—	0.0124	70.5	9.168	2.078	4.89	0.387	0.088	—	—	—
530/AB/23	13.0	1000.0	8.2	0.0126	45.4	5.816	1.319	12.14	0.947	0.215	0.10	0.004	0.001
531/AB/23	13.0	980.0	7.9	0.0052	3.98	1.227	0.278	495.2	92.98	21.08	24.8	2.388	0.541
532/AB/23	18.0	1330.0	11.9	0.0056	16.26	4.624	1.048	28.68	4.966	1.126	—	—	—
533/AB/23	18.0	1325.0	12.7	0.0039	5.79	2.383	0.540	171.7	43.03	9.755	—	—	—

TABLE B-5

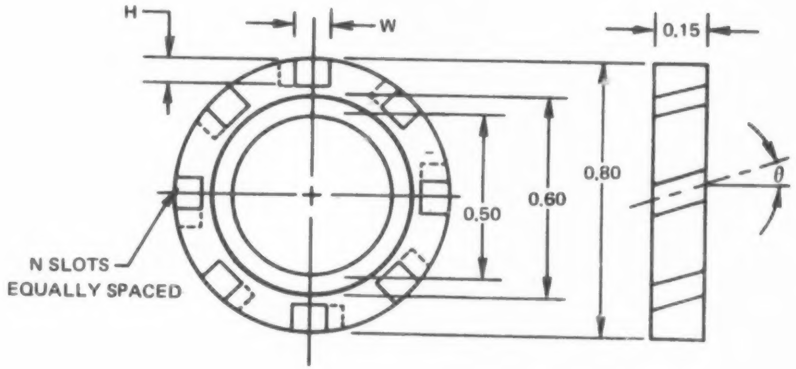
SUMMARY OF FUEL NOZZLES USED ON CLASS UB AND CLASS A/MOD COMBUSTORS

Code No.	Type	Flow No.*	Spray Angle
AB	Air-Blast Atomizer	3.5	85 - 90°
AA	UACL Air-Assist Atomizer	1.0	90 - 95°
PA1	Pressure-Atomizer	2.0	80 - 90°
PA2	Pressure-Atomizer	0.7	80 - 90°
PA3	Pressure-Atomizer	1.9	80 - 90°
DAA	Delavan Air-Assist Atomizer with Integral Air Swirler	1.0	90 - 95°

* Flow No. = $\dfrac{w_{fuel}\ (\mathrm{lb/hr})}{\sqrt{\Delta P\ (\mathrm{lb/in^2})}}$

TABLE B-6

SUMMARY OF AIR-SWIRLER GEOMETRIES USED ON CLASS UB AND CLASS A/MOD COMBUSTORS


H
W
0.15
0.80
0.60
0.50
θ
N SLOTS
EQUALLY SPACED

Code No.	Number of Slots	Height	Width	Angle
	N	H (in.)	W (in.)	θ (deg)
1	8	.080	.080	+30
2	8	.080	.112	+30
3	8	.080	.080	-30
4	16	.080	.080	+30
5	16	.080	.175	+30

Figure B.1 **DELAVAN AIR BLAST ATOMIZER**

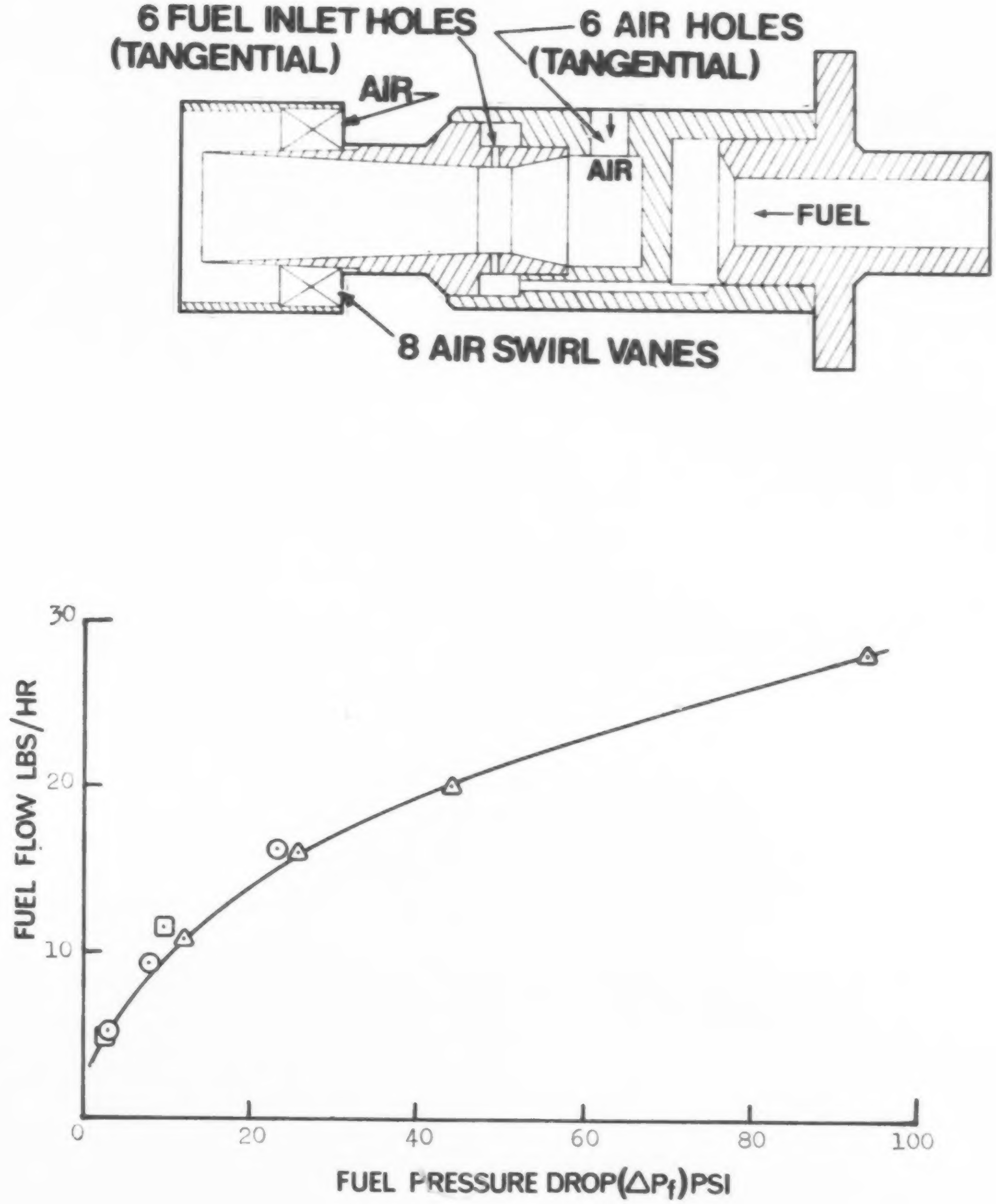

6 FUEL INLET HOLES
(TANGENTIAL)
6 AIR HOLES
(TANGENTIAL)
AIR
AIR
FUEL
8 AIR SWIRL VANES
30
20
10
0
20
40
60
80
100
FUEL FLOW LBS/HR
FUEL PRESSURE DROP(ΔP_f) PSI

FIGURE B-2
EXIT TEMPERATURE DISTRIBUTIONS FROM FINAL CLASS UB COMBUSTOR CONFIGURATION FOR FEDERAL DRIVING CYCLE TEST POINTS